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Final Report *Revised April 1970*

INQUIRY INTO THE ECONOMIC EFFECTS OF AIR POLLUTION ON ELECTRICAL CONTACTS

Prepared for:

DIVISION OF ECONOMIC EFFECTS RESEARCH
NATIONAL AIR POLLUTION CONTROL ADMINISTRATION
1033 WADE AVENUE
RALEIGH, NORTH CAROLINA 27605

Attention: MR. JAMES B. UPHAM

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By: ROBERT C. ROBBINS

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Approved:

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I INTRODUCTION

A significant part of the total cost of air pollution is directly related to the effects of air pollution on materials. The National Air Pollution Control Administration wishes to analyze this cost, and one of the areas of particular interest is the effect of air pollution on electrical contacts. These devices have a special importance because they are components of extensive communications, computer, and instrumentation systems. The highest degree of reliability and performance is required from electrical contacts to obtain satisfactory overall operation in these systems.

The specific goal of this study was to survey, identify, and document problems of economic significance caused by air pollution in the utilization and operation of electrical contacts and other electrical devices. If air pollution does cause problems, they were to be determined and analyzed by searching the literature, by consulting with experts in the field of electrical contact technology, and by consultation with electrical engineers, manufacturers of electrical contacts, and users of electrical devices.

II SCOPE

Contaminants from sources other than air pollution affect electrical contacts and produce the same or similar deleterious effects; therefore, it is important to define the term "air pollution." For the purpose of this report, air pollution is considered to be contamination from external sources, and will include only airborne pollutants whose source is outside the building that houses the electrical contacts.

Electrical contacts are conductor pairs that may carry an electrical current when their separable surfaces are in contact. Contacts are used in switches, relays, connectors, potentiometers, and commutators. Switches are used to interrupt the flow of current in an electrical circuit. A relay is a switch operated by an electromechanical device such as a solenoid. A connector is usually a multiple-contact device permitting the separation of equipment from power sources or from other equipment. A potentiometer, which consists of a contact sliding on a resistive element, is used to vary the flow of current. Finally, a commutator is a disc or cylinder consisting of metal contact segments separated by insulation; a brush contact rides on the segments, making contact with them sequentially as the disc or cylinder rotates.

Contacts are made from a wide variety of materials by a number of techniques. Common materials are precious metals (gold, platinum, palladium, silver), refractory metals (tungsten, molybdenum), and base metals (copper, tin, lead, zinc, aluminum). Occasionally metals are used in the pure state, but more often combinations of metals are used. A contact may be made of a single material, or may be a two-layer structure having bonded or electroplated gold or palladium on a base metal substrate. Electroplated contacts are probably the best compromise between cost and performance.

From the standpoint of contamination, contacts must be differentiated according to the magnitude of the current and voltage being switched. Switching in low-power circuits (millivolts and microamperes) is easily interrupted by thin insulating surface films on contacts. Air pollution-caused films of this type result in poor performance with base

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metal contacts. Therefore, in low-power circuits, contact materials considered resistant to the formation of surface films are usually used. Computers, communications equipment, and electronic instrumentation extensively employ low-power switching.

Although insulating films are troublesome in low-power switching, they generally do not present a problem at higher power levels because the films undergo dielectric breakdown at higher voltage. Much greater amounts of contact contamination are necessary to affect operation under these conditions.

In any assessment of air pollution effects on contacts, it is important to consider the natural surface conditions of various contact metals. For example, an atomically clean copper surface, upon exposure to unpolluted air, immediately forms a layer of oxide several molecules thick. This layer continues to grow but at a progressively slower rate. Hydrogen sulfide, which is a very minor component of the atmosphere, will react with copper to form sulfide in the surface layer. Carbonate from CO_2 may also be included in the surface layer. The background atmospheric aerosol is composed of silica and metal oxides, ammonium sulfate, sodium chloride, and other salts and organic material. This material adds to the surface layer both by deposition and by accelerating corrosive attack. Other base metals will behave in a similar manner when exposed to unpolluted air. All contacts exposed to both unpolluted air and polluted air will show increasing contact resistance with time. The effect of air pollution on contact resistance behavior is therefore one of degree, not of kind. Precious metal contacts will resist corrosive attack but they will, of course, acquire particulate deposits.

While air pollution effects on electrical contacts are the principal interest in this study, significant air pollution effects on any other components of electrical or electronic systems were also of interest. One such area which appears to have economic significance is the effect of air pollution on contamination flashover at the insulators in high voltage transmission systems. Although not called for in the work statement, it was mutually agreed by the technical representative and the author that this effect should be investigated. Contamination flashover can be caused by sea salt, natural dust, and other natural particulate material, but air pollution adds significantly to this problem.

III INFORMATION SOURCES

A. Literature Search

The search for literature on air pollution effects on electrical contacts and contamination flashover was approached from several directions to ensure thorough coverage. In general, material was included if it pertained directly to electrical contact phenomena or to the economics of air pollution of electrical contacts. Initially it was decided that formal coverage of abstracts and indexes would extend back to 1960, and that general literature on corrosion and oxidation would not be covered. These limitations were set because: (1) Air pollution problems of ten or twenty years ago were apt to be quite different than they are today and much of the old literature would not be applicable, and (2) the general literature on corrosion and oxidation was so extensive that covering all of it for a few references pertaining to electrical contacts was prohibitive and inefficient. Rather, it was felt that extensive coverage of citations quoted by key authors would uncover specific corrosion and oxidation references, and would provide any older work that was still useful. This proved to be the case.

The various approaches taken to uncover pertinent literature were the following:

1) A list of more than twenty authors active in the electrical contact field was established on the basis of the frequency of appearance in Electrical and Electronic Abstracts and Applied Science and Technology for the period from 1960 to 1968, and an author search was made for each one covering several literature sources.

2) A list of companies producing electrical contacts, or active in research on electrical contacts, was also established. Searching by company was done for those literature sources which contained corporate author indexes.

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3) Formal abstracting and indexing journals were surveyed and considerable thought was given to choosing all the subject headings that applied to pollution of electrical contacts. If there were cross references leading out of the chosen headings these were investigated to see whether additional information would be found at the new headings. Subject headings change from source to source but, in general, we covered such headings as Air Pollution, Capacitors, Commutators, Contacts, Corrosion (for specific entries only), Flashover, Insulators, Electrical Motors, Electrical Switchgear, Electric Signals, Slip Rings, Coatings (for specific entries only), Finishes, Oxidation (for specific entries only), Dust, Sulfides, Copper, Gold, Nickel, Palladium, Platinum, and Pollution. The specific abstracting and indexing journals covered were:

   - Electrical and Electronics Abstracts, 1960 - May 1968
   - Applied Science and Technology, 1960 - July 1968
   - Chemical Abstracts, 1957 - July 15, 1968
   - Battelle Technical Review, 1967 - Aug. 1968
   - Science Citation Index, 1964 - 2nd Quarter 1968
   - ASTM Review of Metal Literature, 1960 - 1967
   - Current Contents, 1968
   - Business Periodical Index, July 1966 - Dec. 1968
   - TAB, STAR and Nuclear Science Abstracts were searched for authors and corporate authors but subject searching and searching by contract number was done by computer by the agencies themselves.

4) Custom searches were made by DDC, NASA, and AEC by subject as listed above, personal author, corporate author, and contract number.

5) The bibliographies of reprints obtained were checked for more pertinent literature references. If titles were not available, we frequently ordered a reprint of the reference cited in order to check the subject content. Literally thousands of references were considered in this manner.

6) The tables-of-contents of current journals were covered for three to six months back in order to pick up material that might have been missed by abstract journals.

7) Science Citation Index was covered for several key papers. This source allows one to go forward in time as well as backward, and therefore uncovers recent work and new workers in the field.

8) Most of the Holm Seminars on Electrical Contacts were obtained and scanned for pertinent information, as were the International Research Symposia on Electrical Contacts and the CIGRE conferences.

References, by author, title, publication, and date, considered pertinent, were alphabetized according to author and entered in reference notebooks. These references were then procured from our library or from outside sources for screening. The articles that were selected as pertinent after screening were copied, and those reprints entered in a set of reprint notebooks.

The reference notebooks served as a record of what literature had been covered and ordered, and they were mainly used for order records and to avoid duplication. The reprint notebooks were organized by author and chronologically under each author. This provided a brief survey of each author's work and quickly pinpointed work that was missing. The reprints were read and further screened, and those considered most pertinent to the subject were included in the Annotated Bibliography (Appendix A). The remaining references are listed in the General Bibliography (Appendix C).

B. Direct Personal Communication

Companies manufacturing electrical contacts, relays, switches, and connectors; companies manufacturing electrical and electronic instruments; companies using electrical contacts; and electrical power companies were considered as sources of current industrial information concerning air pollution effects on electrical contacts and high voltage power transmission. Technical or research people in these companies were contacted by telephone or letter. Site visits were then made to those people who had a related problem or pertinent information concerning a related problem.

In addition, the 1968 Holm Seminar on Electric Contact Phenomena was attended and discussions were held with a number of people there.

C. Problem Analyses

Most of the information leading to the identification and analysis of the important problem areas was obtained from the technical people contacted. The literature was then used to fill in the technical details, background, and to provide documentation in the analysis of these problems.

IV THE ELECTRICAL CONTACT CONTAMINATION PROBLEM

Electrical contacts can be classified in three groups: (1) light duty contacts required to transmit low voltage and negligible power, (2) contacts carrying moderate currents at moderate voltages, and (3) contacts required to perform heavy duties. The operating problems of heavy duty contacts include erosive and mechanical wear associated with arcing and large forces in contact closure. Heavy duty contacts are essentially immune to contamination. On the other hand, light duty contacts are extremely susceptible to degradation resulting from contamination, since very thin films or very small foreign particles can prevent the occurrence of electricity flow when voltages and closing forces are small.

The three classes of low voltage contacts on the basis of mode of operation are static connectors, sliding contacts, and relays. While each kind of contacts has its own problems of operational design and of wear, they all have the common major problem of high contact resistance caused by surface film [Solov'yeva, et al. (1964) and Freudiger (1962)]. In critical contact application, surface films thicker than 10 angstroms may affect reliability, films of 100 angstroms are completely insulating to contacts operating at less than one volt [Blake (1958)].

In the field of electrical contact applications and technology, contamination effects pose continuing problems to performance reliability. However, air pollution as it is usually defined is generally a relatively minor source of contamination problems. Contamination can reach an electrical contact from at least three sources. The adjacent components in the electrical system in which it is installed can produce contaminant vapors and particles through heating, arcing, or mechanical movement. Because of the closed containers housing most electrical systems, the concentrations of these internally generated contaminants can be quite high. Another source of contact contamination can be the building in which the electrical system is housed and the activities that are present in the area around the device. These contaminants can range from cigarette smoke and floor dust to a wide range of industrial process contaminants that may never reach the atmosphere in any significant concentration. The outside atmosphere provides the third source of contact contamination and can introduce both air pollutants and natural components that may degrade the system. A major natural source of trouble is water vapor.

It should be recognized that the design and application of electrical contacts have evolved in a contaminated environment. Therefore, much of the necessary preventative design is incorporated in the original operating design. In only a few instances has it been possible to identify specific air pollution contaminant problem areas that required corrective engineering action.

As stated above, from the point of view of electrical contact technology, contamination by air pollution is a minor part of the total contamination problem. Sources of contamination from within the immediate environment constitute a much greater threat to reliable contact performance than does air pollution, and the total contamination problem for electrical contacts is severe with many facets. The local environment can cause corrosion, humidity effects, insulating film development, and solid particle contamination.

Fedorov and Zakirov (1964) measured the effect of very thin corrosion films formed by high concentrations of hydrogen sulfide on contact pairs using brass-bronze alloys and brass-Kovar with silver, gold, palladium, and nickel plating. Their interest was in contact aging behavior at very low voltages (203 microvolts) and in the effect of oxide, sulfide, or other insulating films. They found that brass, bronze, silver, and nickel plated contacts that were operated at low voltage levels were severely corroded in atmospheres containing high concentrations of hydrogen sulfide. However, gold and palladium plated contacts were completely satisfactory under these test conditions. Forster and Gebauer (1965) recommended that contact materials for any particular application be selected with care and especially in low voltage use.

Fairweather (1953, 1960, 1962) examined film development on gold, palladium, platinum, and rhodium plated contacts and found that exposure in general service could produce surface films that appeared to be independent of the chemical properties of the metal. These films could be removed easily mechanically by wiping, but in low load, low voltage contact application the presence of the films could cause contact noise and eventual failure. Fairweather did not identify specific pollutants nor the chemical nature of the films, but he did show that oil and dust were present and that there were no corrosion films.

Steading (1965)* describes a particulate contamination survey of 20 offices containing computers. In this survey continuous measurements were made of indoor and outdoor dust loadings. These measurements were made to guide the development of an environmental simulation study of the effects of pollutants on computers. The results showed, not unexpectedly, a wide variation in dust concentrations. Diurnal changes were observed with midmorning and afternoon peaks It was concluded that indoor dust loadings of up to 1,000 micrograms/m^3 were not unusual in computer environments and that significant periods would exceed 500 micrograms/m^3.

Other conclusions reached by Steading relative to the computer environment are:

> Indoor dust levels showed no direct relationship to outdoor dust levels. Air conditioned areas, which many thought gave a cleaner indoor environment, showed the same level as non-air conditioned offices except where special air cleaning equipment was installed.
>
> Traffic through the office area is probably one of the prime factors. In the two-week studies in two locations, we found the daily patterns uniformly repeatable during the work week, and quite different patterns over the weekends when traffic was a minimum. Maximum to minimum ratios of 10:1 were common.

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* See T. W. Steading, J.A.P.C.A. 15(3)99-101, March 1965.

Freudiger (1960), Kaufman et al. (1960), and Mahler (1960) suggested that there were three classes of contamination from at least three different sources. Contaminants might be (1) deposited particles from local or general environment, (2) embedded particles from time of fabrication, or (3) coherent surface films from local or general environment. They point out that wire insulation, plastic components, paints, adhesives, and solder fluxes can release hydrocarbon vapors and corrosive gases. Other contaminants, such as oil droplets or dirt particles, can be introduced at the time of manufacture or cleaning or assembly. Mahler (1960) looked at the particular problem of surface film buildup on palladium contacts in organic vapor contaminated atmospheres, and suggested that silver-cadmium oxide might be a good substitute for palladium in some applications.

Lish (1960) and later Egan (1968) looked carefully at the general contamination problems that occur at the time of contact manufacture. The manufacturing processes can easily contribute to contamination from embedded metal particles. Under conditions that are not meticulously clean, other foreign particles and oil droplets also were found to be contaminants. Sources of contamination during manufacture are the solvent cleaning and washing processes used at the time of assembly and before shipping. These problems have nothing to do with air pollution effects, yet they are important in the area of contact contamination and in many cases might be confused with air pollution effects.

These problems of contamination from sources within the system housing the contact devices occur in all low voltage electrical contact systems, including hermetically sealed contacts. Hyde (1964) described the manufacturing details and cleanliness requirements for fabrication of high quality miniaturized relays that were to be hermetically sealed. He found that it was necessary to be very careful in the selection of insulating and internal structural materials to ensure high reliability in contact operation. Keller (1964) reported that careful selection of component and housing materials in sealed relay systems greatly decreased the contamination potential. He avoided contamination from various organic materials by use of a glass envelope with the leads sealed from the glass and the relays operated magnetically. The use of sealed relays of this type is widespread in the communications industry. This method avoids general contamination and any air pollution effects and results in a major economy. However, the primary reason for sealing the contacts was to provide protection from the local environment in which the devices were used. Again, this is not air pollution as defined in this study. Chaiken (1961) found that in the fabrication of sealed relays, contamination from outgassing of plastic components is difficult to avoid. Unfortunately, sealing relays in an inert atmosphere does not always give successful protection to contact surfaces, because it is so difficult to exclude internal sources of contamination completely. This was described in some detail by Van Auken et al. (1967).

Contacts in moderate duty service show much less sensitivity to contaminants than low voltage contacts, but in the case of palladium contacts fractional polymer buildup can be troublesome in atmospheres contaminated with hydrocarbon vapors [Holm (1967) page 117]. The problem results from the catalytic action of palladium in the polymerization of the organic gases. This process will be described in detail in Section V, Significant Air Pollutants.

Two very important factors in contact contamination are humidity and temperature. High humidity plus high temperature can produce a corrosive environment in the absence of pollutants. For example, the temperature and humidity found in a tropical rain forest would promote corrosion of some electrical contacts in the absence of air pollution. In such a situation the temperature range is 70 to 90°F and the humidity range is from 60 to 100 percent. In the presence of pollutants, humidity is a critical factor, for even when pollution levels are high corrosion rates are very slow at relative humidities below 40 percent. Thus, in the control of air pollution effects on electrical contacts, it is very important to control the humidity and temperature of the local environment. Evans (1948, 1960) in his treatise on metal corrosion outlined the mechanisms of atmospheric corrosion of base metals in great detail. He reported sulfur dioxide to be the most important corrosive agent in pollution atmospheres.

Bloomberg and Campbell (1961) demonstrated that, at humidities above 80 percent but without the deposition of liquid, water caused rapid and extensive corrosion of base metal contacts. In these cases the presence of trace concentrations of gaseous materials, as well as of contaminating surface films, could (or could not) be excluded. The chemical nature of the corrosion films resulting from high humidity were either metal oxides or basic metal oxides.

Bowcott and Cleaver (1962) first surveyed mechanisms of atmospheric corrosion. Dry conditions are usually harmless except when hydrogen sulfide is present; above a certain critical humidity, electrochemical corrosion can occur and is stimulated by gaseous and solid atmospheric contaminants such as sulphur dioxide and soot. Aggressive vapors may evolve from organic insulating and packing materials. Corrosion may be enhanced at bimetallic contacts or where externally applied potential differences exist.

In Bowcott and Cleaver's (1962) discussion, possible effects of corrosion and whisker growth on electrical components are described. Failures may result from disconnections due to corrosion of wires, from prevention of contact and clogging of moving parts by corrosion products, and from the making of unwanted contacts by metal whiskers, corrosion products, and silver migration. The best preventive measure discovered to date is use of a hermetically-sealed enclosure containing a dry uncontaminated inert gas. Other practical steps include air purification, adequate ventilation of enclosed equipment, and avoidance of humid conditions and metal-surface contamination.

Humidity of 80 percent or higher can promote galvanic corrosion under some conditions, but this problem is generally not severe in contact application. In the special case of aluminum connectors, however, all combinations of aluminum with other metals, including aluminum alumina, are susceptible to galvanic corrosion except the combination aluminum-tin [Frant (1961)].

The only contact application in which high humidity may be desirable is in the use of carbon brushes in commutator rings. The water vapor has the role of lubircant and decreases wear, but even here relative humidities as low as 45 percent are adequate [Elsey et al. (1954) and Moberly (1956)].

The kinds of metals used in electrical contacts and their pertinent properties as related to type of contact operation were summarized succinctly by Flatau (1967) in Table I. Blake (1958, 1961) and Chiarenzelli (1966 and 1967) also have reported the results of comparative real time and accelerated corrosion tests of the various metals used in electrical contacts. In a long term, 10-year program under the auspices of the ASTM Committee B-4, extensive field experiments were made that were later augmented by laboratory experiments on real time and accelerated corrosion tests of both base metals and noble metals used in electrical contacts. Their reports represent a large volume of information useful in electrical contact technology.

Industry is making an extensive continuing effort to improve all the aspects of contact technology, using all the available scientific and engineering resources. Several national and international conferences dedicated either wholly or partially to research and development of electrical contacts are held annually. For example, the Holm Seminar on Electrical Contacts and the International Symposium on Electric Contact Phenomena span the spectrum of electrical contact technology. The Electronic Components Symposium, the Annual Symposium on Reliability, and the National Conference on Electromagnetic Relays include considerations of a broader nature, and electrical contacts technology is but one area of interest.

Table 1

CONTACT PROPERTIES OF METALS AND ALLOYS

Contact Material	Silver	Palladium	Platinum	Gold	Copper	Rhodium	Silver-Copper (72-98%)	Silver-Palladium (30-50%)	Tungsten	Rhenium	Silver-Nickel (8-30%)	Silver-Cadmium Oxide (8-15%)	Gold Alloys	Platinum-Gold-Silver (6-69-25%)
Contact Resistance	Low	Low	Low	Very Low	Moderate	Very Low	Moderate	Low	High	Moderate	Moderate	Moderate	Low	Low
Tendency To:														
Oxidize	Nil	Nil Below 400°C	Nil	Nil	High	Nil	Moderate	Nil	High	High	High	Nil	Low	Nil
Sulphide tarnish	High	Nil	Nil	Nil	High	Nil	High	Low	Nil	Nil	High	High	Nil	Nil
Form polymer deposit	Nil	High	Moderate	Low	Nil	Low	Nil	Some	Nil	Nil	Nil	Nil	Nil	Moderate
Weld on closure	Moderate	Low	Nil	High	High	Nil	Low	Low	Nil	Nil	Low	Nil	Low	Low
Resistance To:														
Arc erosion	Moderate	Moderate	Good	Poor	Poor	Poor	Good	Good to Moderate	High	High	Good	Good	Moderate	Moderate
Abrasion	Poor	Moderate	High	Poor	Poor	High	High	Good	High	High	High	Moderate	High	High
Material transfer	Some	Some	Low	Some	High	Some	Some	Some	Nil	Nil	Low	Low	Low	Low
Available in all shapes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes
Cost	Low	High	Very High	High	Very Low	Very High	Low	Low	Moderate	Very High	Moderate	Moderate	High	High
Remarks	Associated insulants must be chosen with care to guard against silver migration (Ref. 19)			Usually used as coating or overlay		Used as coating only			Corrodes in the presence of some organic materials	Oxides unstable and low resistance			Alloying elements Pt, Ni, Si, Co or Ag.	*

From: G. Flatau, Reliable contacts and connections in the telecommunications plant. Inst. Elec. Engr. Trans. (Australia), EE-3(1), 59-67 (Mar. 1967).

V SIGNIFICANT AIR POLLUTANTS

A. Sulfur Gases

Much more money is spent combatting the effects of SO_2 and H_2S pollution on low voltage electrical contacts than is spent on all the other air pollution effects on electrical devices combined. As always, the picture is complicated by a number of factors. First, it is difficult to make a quantitative separation between natural and man made H_2S; and also, the presence and concentrations of other atmospheric components, not necessarily pollutants, have a profound influence on the corrosive potential of the sulfur gases. The most important of these components is water vapor; however, oxidants, particulate metal oxides, and organic droplets that settle on contact surfaces all tend to promote sulfur gas corrosion by producing sulfuric acid or acid salts held in intimate contact with surfaces.

During the past 20 years, a great deal of effort has been directed to the study of the mechanisms of sulfur gas attack on metal surfaces, including specific studies of electrical contact systems; silver, copper, gold plated copper, gold plated copper with nickel diffusion barrier, and many other surfaces. The papers of Phillips (1962), Halstrom (1961), and Snowball et al. (1967) are among the more important ones where the specific attack mechanisms leading to contact failure were examined.

Campbell (1965) and Campbell and Thomas (1968) have studied the mechanisms and rates of tarnishing and corrosion of copper and silver over a period of many years. They have found that copper tarnishes much more rapidly than silver in atmospheres containing H_2S. It reacts with very dry H_2S, while silver does not. Silver is unreactive to SO_2 even at high humidity, but copper reacts rapidly. A dry atmosphere containing both H_2S and SO_2 causes rapid reaction with both copper and silver.

This empirical information suggests that sulfur gas attack on copper and silver occurs by different mechanisms and that free sulfur vapor is the silver tarnish component of the atmosphere and that it is produced by the reaction

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \qquad \Delta F = -11.72 \text{ Kcal(exothermic)} \qquad (1)$$

or

$$2H_2S + O_2 \text{ (in presence of water vapor)} \rightarrow 2S + 2H_2O$$
$$\Delta F = -93.5 \text{ Kcal(exothermic)} \qquad (2)$$

The kinetics of these reactions have not been studied; however, it can be inferred from the corrosion studies of Campbell and Thomas (1968) that reaction (1) is about ten times faster than reaction (2) at room temperature.

The saturation vapor pressure of sulfur at 25°C is 2×10^{-5} mm Hg, which is equivalent to about 20 ppb of sulfur vapor in the atmosphere. When the combined concentrations of H_2S and SO_2 are higher than 20 ppb, the excess sulfur forms an aerosol of submicron particles. This sulfur aerosol behaves both chemically and physically like sulfur vapor, except that it is filterable.

The elemental sulfur attack hypothesis was confirmed by passing New York City air through pumice soaked in lead acetate and then over a silver surface. Any H_2S was completely removed by the lead acetate, but the silver tarnished at the same rate as it would in untreated air. It is concluded that the sulfur passed through the pumice and was responsible for the resulting tarnish.

Campbell and Thomas (1968) also investigated the nature of the films produced on copper and silver in polluted air. The copper corrosion film was composed of CuS with a small amount of CuO. As the film grew, the CuS/CuO ratio remained constant. Silver tarnish was found to be Ag_2S with a trace of Ag_2SO_4.

Abbott (1968) has also studied copper and silver tarnishing in the laboratory. He added H_2S, SO_2, and also elemental sulfur at realistic pollutant concentration (1-100 ppb) to a synthetic air, 80 percent N_2, 20 percent O_2. Water vapor was added to produce different relative humidities to a maximum of 90 percent.

The growth of Ag_2S followed a linear rate law to film thickness of at least 0.2 micron. Analysis of the film material on silver and copper, tarnished with H_2S or S, revealed that Ag_2S and CuS were the principal products. CuO was found in the Cu tarnish and traces of Ag_2SO_4 were found in the Ag_2S.

An effect that has produced serious contact problems was first recognized and studied by Egan and Mendizza (1960) and Frant (1960). Where contacts containing silver under gold or silver solder leads to gold contacts are exposed to a tarnishing atmosphere, the Ag_2S formed will creep through pores in the gold plating and across boundaries onto gold survaces. Silver sulfide adheres more strongly to gold than to silver [Antler (1966), Keil (1963), and Harding (1960)]. Such a development would negate the added investment made in the gold contact surfaces.

Antler, Barte, and Brumbein (1967) have evaluated gold plated contacts for corrosion resistance and creep and have shown that smoothness of the substrate surface is very important, as is a diffusion barrier underplate between the substrate and the gold film. They also showed that pore blocking corrosion inhibitors used with compatible lubricants help in the isolation of the base metal substrate with a minimum thickness of gold plate [Brumbein and Antler (1967)]. Paraffin and polyphenol ethers have shown promise as lubricants for gold plated contacts without adverse corrosion or creep side effects, according to Antler (1967) and Chiarenzelli (1966).

Since there are no direct experimental studies of real air pollution effects on electrical contacts, field studies of nonferrous metal corrosion are probably the best available means of assessing air pollution of base metal contacts without further experimental studies. The state of the art summary by Yocum and McCaldin (1968)* indicates that the corrosiveness of urban atmospheres toward many metals has greater dependence on sulfur dioxide concentration and humidity than any other factor.

Using zinc as a typical nonferrous metal, the American Society for Testing Materials compared the corrosiveness of various rural, urban, and marine atmospheres in hot, moderate, and cold climates in 37 locations in Europe and North America [Larrabee (1961)]. The weight loss occurring to 4-by-6-inch zinc specimens was measured after exposure for one year. State College, Pa., was taken as a standard rural (clean) atmosphere. The most severe corrosion occurred in the industrial atmopheres of Newark, N.J., Bayonne, N.J., and London, England; each produced two to four times the zinc corrosion that occurred at State College. Very little corrosion occurred in cold, rural areas. Probably the most significant finding was the wide local differences, which appeared to depend on the sample location relative to the major pollution sources. Lodge and Havlik (1960) and Lodge and Frank (1962) developed a more sensitive method of determining atmospheric corrosivity by measuring the amount of attack on thin evaporated metal films.

B. Organic Gases

The most important air pollution effect on electrical contacts relating to organic gases is the "frictional" polymer formation on sliding or wiping palladium contacts.

The so-called "frictional" polymer was first studied and identified by Hermance and Egan (1958) because of the fact that telephone switching relays using palladium contacts were noticed to be subject to transient closure failures. When this occurred, a dark brownish deposit was always found on the contacts. A study of the formation mechanism and composition of the material revealed that it was formed from organic vapors, it was entirely organic, and its formation rate was proportional to the number of cycles of contact operation or the amount of rubbing or wiping of the contact surface. Hermance and Egan (1958) showed that organic vapors were the reacting species and that a polymerization reaction was catalyzed by the palladium and strongly promoted by the rubbing action between the contacts.

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* J. E. Yocum and R. O. McCaldin, "Effects of Air Pollution on Materials and the Economy," Chapter 15, Vol. 1, Second Edition, Air Pollution, A.C. Stern (Ed). Academic Press, New York, 1968.

They also found that a small amount of polymer was beneficial, since wear was reduced without greatly changing the electrical conductivity, and that the detrimental effects were due to excessive accumulations of material.

The phenomenon of organic polymer formation has been intensively and extensively studied during the past decade. In addition to Hermance and Egan (1958) and Chaiken (1961), Campbell and Lee (1962) have investigated various aspects of the problem. Palladium and other platinum family metals are surface catalysts for this reaction, which proceeds slowly on static surfaces and is greatly accelerated by the rubbing or wiping action of operating contacts [Mader (1966) and Fairweather (1966)].

In operational practice, the hydrocarbon vapor is usually produced by the outgassing of insulation and other plastic components in the electrical system, and only a very small part of polymer formation on telephone relay contacts can be attributed to air pollution.

During investigation of the frictional polymer problem, a number of possible solutions were suggested. Chaikin (1963) noted that lead and iodine compounds inhibited polymer formation. Gold is a poor polymer producer and alloying palladium with gold greatly decreases the formation of polymer. Ruthenium appears to be an inhibitor. In a discussion concerning polymer inhibition by ruthenium, W. Doherty of Microdot in South Pasadena, California, reported a recent claim that 4 percent ruthenium in palladium completely inhibits polymer formation.

The frictional polymer problem was very serious for the telephone companies in the 1950-60 period, and the cost of controlling the problem was large. The program to combat this problem was one of the first in which a great deal of money was spent on research and engineering directed specifically at eliminating a problem concerning possible air pollution effects on electrical contacts.

A second minor organic gas effect occurs with medium voltage contacts. Hydrocarbon vapor is carbonized by arc heating during relay operation, and the carbon layer produced intensifies and changes the character of the contact arc. This effect was examined by Campbell (1962) and Germer and Smith (1957 and 1958). The effect is called "contact activation." The deposited carbon lowers the minimum arcing potential and greatly increases arcing time per operation and thus leads to greatly increased erosion damage to the contact surfaces.

Again, the fraction of erosion failures due to general atmospheric organic gases is small, since outgassing of insulation and other plastic components cause at least 80 percent of the contact activation problems.

C. Particulate Pollutants

In urban areas, the atmospheric aerosol generally contains corrosive components as shown by Keefer (1957), Maddock et al. (1957), and Williamson et al. (1956); and the effects of particulate material from air pollution on electrical contacts are almost entirely chemical rather than physical or mechanical. The urban aerosol also is usually an excellent adsorbent of corrosive gases and water vapor, both while suspended as an aerosol and also after deposition. Chiarenzelli (1963), in studying the effect of particulate pollutants on electrical contacts, analyzed, over a period of many months, the material collected in one New York location on a fiberglass filter. He found ferric chloride to be the main corrosive component. Other analyses of collected particulate from the New York area show sulfate as the major anion, with iron and ammonium as the main cations plus significant fractions of magnesium, lead, titanium, vanadium, and copper. This material is hygroscopic and mildly corrosive to copper at 60 percent relative humidity; at 80 percent, it is severely corrosive to copper. Several investigators over the past several years have reported that the New York aerosol causes nickel "fogging." This is believed to be due to a catalytic oxidation reaction at the surface, producing a nickel sulfate-nickel hydroxide film.

A most direct and unambiguous example of an air pollution effect on electrical contacts was the stress corrosion cracking of wire spring relays in telephone relay stations in Los Angeles. Pacific Bell Telephone became aware of this particular pollution problem around 1965 when their wire spring relays started breaking in large numbers. Stress corrosion is a corrosion process that is enhanced by the presence of stresses along the affected surface and generally caused failure on a single deep crack in the surface.

Bell Laboratories was given the job of finding the cause of the trouble and suggesting the best countermeasures. The investigators from Bell Laboratories quickly diagnosed the problem and showed that high nitrate dust, rising from the reaction of the smog component nitrogen dioxide along with other materials in the atmospheric nitrate in the Los Angeles aerosol was producing the stress corrosion. When settling on the wire springs, this dust caused stress corrosion cracking at humidities higher than 50 percent. The copper-zinc-nickel alloy used in the wire spring was uniquely affected by the combination of high nitrate dust, high humidity, and positive potential. Field and laboratory experiments were made, exposing wire spring assemblies to various conditions of dust composition and humidity. These experiments showed that cracking rate depended on both nitrate concentration in the deposited dust and the relative humidity. Nitrate surface concentrations of 20 to 70 micrograms per square inch, which were found in Los Angeles, caused stress corrosion cracking at relative humidities above 50 percent. Bell Telephone changed its wire spring alloy composition and also installed high efficiency filters, dehumidifiers, and air conditioners on the air intakes of exchanges having the old wire springs [Hermance (1966) and McKinney and Hermance (1967)].

As air pollution has increased and spread to outlying areas and other cities in California, Pacific Bell Telephone has prevented a parallel increase and spread of wire spring failure with the installation of filter-dehumidifier-air conditioners before nitrate dust levels became critical. These facilities represent an investment of about $3 million based on an estimate of Mr. R. Duske of the Pacific Bell Telephone Engineering Department.

Urban areas in California are beginning to notice nitrate corrosion effects not only on wire springs but also in nickel bases of palladium-coated contacts of crossbar switches. Corrosion products formed in the nickel bases tend to creep over the palladium contact surfaces. Other cities where this condition has recently been noticed are New York, Philadelphia, Cincinnati, Detroit, and Cleveland. Filtration and dehumidification also will be used to eliminate this problem.*

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* See H.W. Hermance, C. A. Russell, E. J. Bauer, T. F. Egan, and H. V. Wadlow, "Relation of Airborne Nitrate to Telephone Equipment Damage" (in press).

VI ECONOMIC EFFECTS

The previous discussion indicated that adverse environmental effects on electrical contacts may be countered in two general ways. The contact can be protected from the environment either by sealing the individual components on the installation of air purification equipment. Alternatively, the contact can be engineered so as to be significantly less sensitive to environmental factors. This has generally required the substitution of precious metals such as gold or palladium for cheaper base metals such as copper, brass, or silver. The following discussion presents an appraisal of the economic impact on the electrical contact industry of these and other factors related to environmental problems. As previously mentioned, air pollution effects are usually not separable from other environmental factors, and in most cases it has been necessary to substitute estimates instead of calculated values in arriving at the economic impact of air pollution.

A. Uses of Precious Metals

When gold or palladium are used in contacts, it represents a significant cost factor for the component compared with the component costs when base metals are used. Thus the market prices of the precious metals have had a bearing on the contact industry and provide an impetus for research that may lead to the use of base metals without a loss of reliability. The cost differentials between palladium and gold have over the past years favored the use of palladium; however, the relative difference sometimes has been fairly small.

For the last four or five years, most of the electrical contacts and connector manufacturers have taken the attitude that for low voltage contacts and connectors, when thin tarnish or corrosion films pose a real threat to contact or connector reliability, thick gold or palladium plate was the answer [Fairweather et al. (1962), Angus (1962), Shtremberg and

Gayevskaya (1964), and Chaston (1967)]. Therefore, the trend has been to gold plate contact with 100 to 200 microinches of gold, Ball et al. (1968), and the consumption of gold in the United States has increased rather sharply from 500,000 ounces in 1963 to 2 million ounces in 1968. The value of the gold and platinum metals (mostly palladium) used in electrical contacts in 1968 was almost $140 million (estimated from Annual Report of the Secretary of the Treasury, 1967). Even with this recent large increase in use, most of the precious metal was used to minimize the effect of local contamination from sources other than air pollution. Only 10 to 20 percent was used to combat air pollution, according to an estimate generally agreed on by experts in the industry, among them, J. H. Whitley, AMP, Inc., and V. G. Mooradian, Engelhard, Inc. Thus, the precious metal cost attributable to air pollution in the United States for 1968 must be considered to be no more than $20 million.

During the period 1961 to 1968, the price of palladium rose from $24/Troy oz to a peak of $45/Troy oz, making palladium less attractive but still less costly than gold as a contact plating material. In February, 1969, the price of palladium started down, reversing the five-year trend. Palladium prices between 1961 and 1969 are given in the following schedule.*

Date	Price $/Troy oz
December 1961	$24
January 1964	26
February 1964	27
March 1964	31
December 1964	32
June 1966	33
October 1966	35
January 1967	37
February 1968	39
March 1968	42
June 1968	45
February 1969	43
November 1969	37

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* Supplied by Engelhard Industries.

During this time, the price of gold was almost constant at the government's fixed price of $35/Troy oz. Four four months in 1968 the price of gold in this country rose to about $40/Troy oz but then returned to about $35/Troy oz.

Since the density of palladium is 12.0 and that of gold is 19.3, the price of palladium would have to rise to $56/Troy oz to be as expensive as gold on a volume basis, i.e., 35 x 19.3/12/0 = 56. At the pre-1964 price, palladium at that time was 43 percent as costly as gold by volume.

The electrical contact industry is actively seeking new solutions to the contamination and corrosion problems. At least some of the research and development people believe that, in spite of increasing air pollution, low voltage contacts made of base metal can be made to perform at desired levels of reliability by using appropriate design concepts.

One such approach using high pressure electrical contacts has been suggested by King (1967). By the simple expedient of optimum mating and surface design and the use of relatively high closing pressures, he has demonstrated that base metal contacts can be operated in polluted atmospheres without excessive wear by penetrating the corrosion film with each contact closure.

Another important new development that is already reducing the demand for palladium in electrical contacts is electronic switching in telephone relay systems.

B. Protection of Low Voltage Contacts

The use of computers and sophisticated electronic control systems in the United States has expanded at a rate of about 30 percent per year for the past three years. The gross value of this electronic equipment installed in 1968 was about $3 billion (U.S. Census Bureau, Annual Survey of Manufacturers, Value of Shipments of Product Classes 27, 29, 1967).

Reliability of operation of this expensive equipment is of primary importance, as pointed out by Bryant (1968), Atkinson (1964), and

New (1960). Failure of electrical contacts during operation because of air pollution effects could quickly jeopardize all this important reliability. An estimate of the economic loss due to the contact failure in communications, computer, and instrumentation systems in the United States is difficult to make. Atkinson (1964) measured a contact failure rate of one per million contacts for electrical systems in commercial jets. A very rough guess, extrapolating Atkinson's reliability factor, indicates that this loss must be less than $10 million a year, including direct loss, downtime, maintenance, and parts costs.

Manufacturers of computer systems attempt to minimize air pollution effects by using precious metal contacts and by including air conditioning facilities in the computer system. This process has been described by Wagner et al. (1961) and Blake (1959). It is desirable and frequently necessary to cool and dehumidify the air for these electronic systems even where air pollution is absent. As SRI estimate of the cost of air conditioning equipment for computers, communications, and other electronic systems is $250 million per year in the United States. This includes activated carbon filters and high efficiency fine particle filters which are used in a few urban areas such as Los Angeles. The SRI estimate is that the cost of air conditioning and purification equipment assignable to air pollution is about one-tenth of the total cost of the air purification equipment used with electrical systems, or $25 million.

The value of high efficiency filters constitutes a relatively large fraction (25 percent) and the value of activated carbon filters a relatively small fraction (5 percent) of the chargeable air purification costs, since very few manufacturers or users have yet resorted to activated carbon filters. A greater expenditure is probably justifiable.

C. Research Costs

One air pollution cost to electrical devices that must be considered is the money spent on research and development to eliminate or minimize the effects of air pollution on these devices. This cost is made up primarily of the research budgets of the manufacturers and large users of contacts and high voltage transmission systems. A dollar value can be derived from this cost by taking 2 percent of the value of the estimated annual sales of low voltage contacts. The 2 percent is believed to represent the fraction of total income invested in air pollution research by the contact industry. Based on estimates and predictions by R. C. Sprague, made in Electronic News, p. 54, June 10, 1968, a best figure for 1968 sales of low voltage contacts is about $250 million. From this we arrive at a research cost for air pollution in the contact industry of $5 million. This number does not take into account high voltage transmission research costs for air pollution which are much smaller, not more than $1 million and more likely about $500,000.

Research costs for air pollution effects on electrical contacts may increase during the next few years as more general and more economical approaches are sought and developed to eliminate these effects. At the same time while these costs are rising, they should be more than offset by the decrease in manufacturing and maintenance costs in the industry.

D. Protection for High Voltage Transmission

When it became apparent during the study that "flashover" of high voltage transmission lines due to solid pollutants also presented a significant economic problem, this problem was included. The air pollution costs to high voltage power transmission are essentially embodied in the measures taken to prevent contamination flashover, i.e., "hot washing." Southern California Edison Company's cost for this was reported in Electric Light and Power, August 1969, page 43. The estimated cost at SCE for 1969 is $1 million. Since SCE represents about 5 percent of the electric power industry, the cost for the entire country can be conservatively estimated to be ten times this amount. Forrest et al. (1960) made an analysis of contamination flashover frequency in terms of sea salt contamination versus total contamination in the United Kingdom. This analysis showed 40 percent contamination flashovers due to industrial pollution. Extrapolating this fraction to the United States and using $10 million as an estimated washing cost, the annual cost of air pollution in contamination flashover is about $4 million at the present time. A more detailed discussion of this problem is contained in the following section.

E. Discussion

Considerable effort and money is being invested in trying to improve the air pollution conditions in urban areas. However, if air pollution levels were to decrease in the next decade to 50 percent of the present urban air pollution levels, the effect of this new condition on air pollution costs to the electrical contact industry would be very small. Essentially the same preventive measures and same programs at the same rates of effort would be expected to proceed for a number of years. Furthermore, protection would still have to be maintained against possible adverse conditions in the internal system and in the indoor environment. It is conceivable that after a relatively long lag time a continuing low level of urban air pollution may provide a basis for some adjustments in measures and programs leading to somewhat decreased air pollution costs in the electrical contact industry. For the present time, however, industry does not know at what level air pollution would have to be maintained to realize economic savings through design and material changes and reduced research, protection, and failure.

In summary, the economic costs of air pollution on the electrical contact and electric power industries as described above are (in millions of dollars):

Protection of contacts	$25
Use of precious metals	20
Loss due to failures	10
Research	5
High voltage flashover	4
	$64

VII AIR POLLUTION EFFECTS ON HIGH VOLTAGE POWER TRANSMISSION

The air pollution problem relating to high voltage power transmission was included in this evaluation because it appeared to be significant in connection with the economics of electrical devices.

Insulator flashover in humid and polluted atmospheres is a major transmission line problem. This kind of flashover is called contamination flashover as opposed to flashover caused by atmospheric ionization during thunderstorms. The mechanisms involved in producing contamination flashover are complex and only partially elucidated even though the phenomenon has been studied for many years [Hampton (1964), Ely and Lambeth (1964), Fujitaka et al. (1968), and Kawai (1968)]. In recent years the power companies have gradually increased transmission line voltages from about 250 kV to as high as 750 kV as their power requirements increased (Gothberg et al., 1968). In doing this the contamination flashover problem has become intrinsically much more severe, and it has been necessary to improve insulator design continually. It is known that contamination flashover occurs when insulator surfaces, which have deposited layers of material from the atmosphere, are wetted by high humidity, fog, or rain. Alston and Zoledziowski (1963) have analyzed this phenomenon and shown that a minimum conductance gradient through the contaminant layer is required. Much contamination flashover is caused by deposited sea salt in regions where salt aerosol concentrations are high. Silica and silicate dust are not as liable to cause flashover as salt or certain deliquescent air pollutants. In recent years the particulate burden in industrial areas composed mostly of soot, fly ash, sulfur compounds, coal dust, and cement dust, adding to the loading on high voltage insulators, has caused contamination flashover to become a severe problem in those areas downwind of the sources [Ely and Roberts (1968)].

In many areas in the northern U.S., calcium chloride is used on highways to remove snow and ice. During the spring and summer, much of this $CaCl_2$ is picked up by the winds and some of it is deposited on high voltage insulators to become a particularly troublesome contamination component. This was reported by M. Kawai in 1968 at the General Electric UHV Laboratory in Pittsfield, Massachusetts.

A number of methods have been developed to minimize contamination flashover [Lambeth (1964)]. Oil or grease films have been used; silicon grease was found to be effective but expensive [Lambeth et al. (1966), Ignacz (1962), and Harris (1954)]. The most successful measure appears to to be "hot washing," i.e., washing the insulators with very high pressure streams of water without interrupting service, on a preventive schedule [Last et al. (1966), Gaiennie (1960), and Hill (1947)].

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VIII SUMMARY

Prevention of contact failure in low voltage contacts is the largest problem area in which air pollution effects on electrical contacts are found. Millions of low voltage contacts are used in computer and instrumentation circuits, and some provision must be made to ensure their reliable and continued operation. The sulfur gases are primarily responsible for the deleterious effect of air pollution on these contacts. More money is spent in the protection of low voltage contacts against the effects of sulfur gases than in all the other contact problem areas combined.

Protection of low voltage contacts against sulfur gases takes two forms. One form of protection is the use of air conditioning and air purification equipment to minimize or eliminate sulfur gas effects on contacts. All computer systems and most instrumentation systems now include air conditioning, and some of these systems have high efficiency particulate and activated-charcoal filter combinations added. The total cost of this air conditioning and purification equipment for 1968 in the United States was about $250 million. The fraction of this cost assignable to air pollution is somewhat arbitrary, since the air conditioning would have been provided in the absence of air pollution. A tenth of the air conditioning-purification cost, or $25 million, is a conservative estimate of the fraction changeable to control of air pollution effects.

and

The other kind of protection of contacts against sulfur gases is precious metal plating. The estimated value of gold and platinum used in electrical contacts in the United States in 1968 was $140 million. Of this total amount, according to industry estimates, only about 15 percent or $20 million, was used to combat air pollution. The larger fraction (85 percent) of precious metal was used to counteract specific contaminants from sources other than air pollution.

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The use of precious metals in electrical contacts should be reduced in the near future, because new operational and design techniques are now being developed within the industry that should give base metal contacts satisfactory performance characteristics in hostile environments.

Palladium is used in many electrical contact applications; it is corrosion-resistant and has excellent wear properties. However, hydrocarbon vapors present in the air around contacts will polymerize on palladium and palladium alloy surfaces. This produces insulating films and loose powder, which occurs because palladium is a polymerization catalyst for many organic compounds. In telephone switching relays, the polymerized organic material is referred to as "frictional" polymer because its formation is greatly accelerated by rubbing or wiping during contact operation. Large amounts of this polymer on contact surfaces cause failure by introducing a high resistance. The communications industry has chosen to meet this problem by removing hydrocarbon vapor from local environment rather than discontinue use of palladium.

Palladium contacts, which may age several months or years before being called on to operate, present a special problem. During any part of the stand-by interval, exposure to hydrocarbon vapors may cause a polymer film to form and grow. A contact so coated is liable to fail during its first operation.

Another palladium contact-polymer problem entails accelerated contact erosion due to "contact activation" of arcing contacts. The organic material is carbonized by arc heating, and the carbon layer increases the arcing intensity that leads to erosion damage.

The communications industry has used gold electroplated on silver in some contact applications. When exposed to hydrogen sulfide, the silver sulfide formed may migrate through microscopic pores in the gold electroplate and foul the gold contact surface with an adherent silver sulfide film.

Economic loss due to contact failure is difficult to estimate but, because of the relatively good reliability in today's contacts, is probably no more than $10 million a year in the United States. This

$10 million is the economic loss due to contact failure only, such as equipment downtime, repair, and parts costs; the larger economic loss is the high cost of achieving this reliability. Much of the research today is directed toward getting equal or better reliability from cheaper contacts. Therefore, a major saving will result from lower manufacturing costs of contacts that will give reliability as high as or higher than today's plated contacts under similar pollution conditions.

The annual cost of research and development of air pollution effects on electrical contacts is about $5 million in the United States. This cost is expected to increase in the next few years as the contact industry expands and as new approaches to eliminating air polution effects are sought.

At the present time, air pollution costs related to electrical devices are unnecessarily high because in most of the problem areas, two or more effective countermeasures are being applied simultaneously. This overreaction is a response to the reliability problem in electrical contacts which became serious and troublesome a few years ago.

A listing of these current costs in millions of dollars shows:

Protection of contacts	$25
Use of precious metals	20
Loss due to failures	10
Research	5
Hivoltage flashover	4
Total	$64

Thus, while the cost relating to failure of electrical devices caused by air pollution for 1968 is estimated to be about $64 million in the United States, more selective use of the most efficient measures to eliminate air pollution effects could have reduced this cost.

It is felt that reducing current air pollution by 50 percent would have little effect on air pollution costs related to electrical devices, because any reduced level of recognized air pollution would still require that measures taken to combat air pollution effects be continued at the same level of effort. Industry does not know the amount of air pollution reduction needed to appreciably reduce the damaging effects on electrical contacts.

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

Abbott, W. H. and H. R. Ogden. Electrical contact materials in low current technology, Battelle Tech. Rev. 14 (3), 17-22 (1965).

Low-current contacts are of prime importance because of their influence on the reliability of vital electronic systems. Future improvements will depend on extending the basic knowledge about material properties and contact phenomena. The causes of failure of various types of contacts and factors involved in designing materials for improved devices are discussed.

Abbott, W. H. The mechanism of tarnishing of silver and copper, In: Electrical Contacts, 1968, Proc. Engineering Seminar on Electrical Contact Phenomena, Illinois Institute of Technology, Chicago, Ill., Nov. 11-15, 1968, pp. 53-4.

A study was made of the effects of environment on the tarnishing reactions of high purity silver and copper. The objectives of the research were (1) to determine the composition of the surface films formed under several environmental conditions, and (2) to relate film composition and/or structure to contact resistance characteristics.

Alston, L. L. and S. Zoledziowski. Growth of Discharges on polluted insulation, Proc. Inst. Elec. Engrs. 110 (7), 1260-6 (1963).

The voltage required to maintain local discharges on polluted insulation may increase with increase in discharge length, and if this voltage exceeds the supply voltage, the discharges extinguish without causing a flashover.

Angus, H. C. Surface films on precious-metal contacts. Brit. J. Appl. Phys. 13, 58-63 (1962).

A study of incidence and behavior of thin films on platinum metal surfaces by measuring contact resistance at 1 mg to 5 gm loadings.

Antler, M. and J. Gilbert. The effects of air pollution on electric contacts, J. Air Poll. Cont. Assoc. 13 (9), 405-15+ (1963).

A thorough review of the various effects of air pollution on contacts including field and laboratory information and an interpretation of the basic physics and chemistry involved.

Antler, M. Current topics in the surface chemistry of electric contacts, IEEE Trans. Parts, Mater., Pkg PMP-2 (3), 59-67 (1966).

This paper describes recent work in the science of the separable electronic pressure contact with emphasis on chemical factors in performance. The following topics are discussed: growth and morphology of sulfide tarnish films which creep across the interface between gold plate and silver or copper alloys and degrade

contact performance; the formation and structure of corrosion solids on porous gold electroplated contacts, and which originate in atmospheres polluted with sulfur dioxide or hydroscopic dusts; new developments in measuring the porosity in precious metal plates; the critical dependence of the porosity of gold plate on substrate roughness; and new concepts for developing electronic connectors with contacts made of base metals.

Antler, M. Current research in the precious metal plating of electric contacts, Plating 54 (8), 915-22 (1967).

A new method for reducing the corrosion of thin, hence porous, gold plates on basic metals and underplates (e.g., nickel) is presented. Organic coatings were developed which do not significantly increase the contact resistance of the gold. In addition to corrosion inhibition, they effectively lubricate contacts, and so minimize wear-induced porosity of the plate.

Antler, M., S. M. Garte and S. J. Krumbein. Recent studies of the contact properties of gold plate, In: Electrical Contacts, 1967, Proc. Engineering Seminar on Electrical Contact Phenomena, Illinois Institute of Technology, Chicago, Ill., Nov. 6-9, 1967, pp. 79-92.

High reliability contacts with a minimum of gold plate can be produced by using (1) smooth substrates, (2) an underplate, or system of underplates, chosen to minimize substrate diffusion and reduce the intrinsic porosity of the gold plate, (3) pore-blocking corrosion-inhibitor coatings, and (4) compatible lubricants having a liquid component.

Atkinson, J. E. Environment-resistant connector field reliability report, IEEE Trans. Reliability R-13 (2), 8-15 (1964).

4×10^8 connector operating hours were logged in 173 commercial jet airplanes. Connector failure rates averaged one per 10^6 cycles.

Baker, R. S. Studies of static low voltage contacts at the Bell Telephone Laboratories, In: Second International Conference on Electrical Contacts, Graz, Austria, May 4-6, 1964. 35 pp.

The effect of atmospheric exposure on various electroplated coatings for possible use in separable static connectors has been studied.

The wear behavior on crossed cylinders and on actual production equipment plated with various coatings has been measured.

The best protection during atmospheric exposure is provided by precious metal coatings thick enough to be pore free. A composite coating of gold-rhodium-nickel has outstanding wear resisting properties. Hard alloy golds plated from acid baths are also highly resistant to wear. Soft 24-carat gold and 50% tin-lead coatings are likely to gall and exhibit a high degree of wear even at light contact forces; however, the use of lubricants during the wear-in period can eliminate rapid initial galling.

Ball, M., F. H. Hardie and E. J. Struckus. Increase connector contact reliability, Electron. Engr. 27, 82-5 (March 1968).

For aerospace applications the authors recommend gold on nickel as the contact material with an increase in thickness of the gold plating from the standard 50 mils to about 150 mils.

Blake, B. E. Some measurements of contact resistance in an accelerating air atmosphere, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1958, pp. 1-6.

The effects on contact resistance of contact material, loading, and contact shape for crossed-wire contacts of aging in accelerating atmospheres were studied. Measurements of copper tarnish film thicknesses were made comparing normal growth rates with accelerated growth rates.

Blake, B. E. Dry circuit contacts, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1959, pp. 85-94.

The problems of low voltage contact operation are discussed.

Blake, B. E. and M. A. Oliver. Progress report on the activities of Section G of ASTM Committee B-4, Sub-committee IV, IBM Corp., Poughkeepsie, N.Y., June 1961, 35 pp.

Blake, B. E. Summary report of the ASTM Section G contact field tests, Components Div., IBM Corp., Poughkeepsie, N.Y., 14 pp.

Test pieces of copper, beryllium copper, brass, nickel, tin lead, silver, palladium, and gold were exposed for 2.2 years at Newark, N.J., and Kure Beach, N.C.

Bloomberg, J. and W. E. Campbell. Effects of atmospheric contamination on switching noise, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 11-15, 1961, pp. 95-108.

The effects of humidity on the chemical activity of traces of corrosive gases was studied in the laboratory.

Bloomberg, J. and W. E. Campbell. Further studies of sliding contact noise, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 11-15, 1961, pp. 109-13.

The above study was extended to include field data.

Bowcott, H. J. and A. J. Cleaver. Corrosion of electrical components by their atmospheric environment, Proc. Inst. Elec. Engrs. B-109, Suppl. 22, 559-66 (1962).

Mechanisms of atmospheric corrosion are first surveyed. Dry conditions are usually harmless except when hydrogen sulphide is present; above a certain critical humidity, electrochemical corrosion can occur, and is stimulated by gaseous and solid atmospheric

contaminants such as sulphur dioxide and soot. Aggressive vapours may be evolved by organic insulating and packing materials. Corrosion may be enhanced at bimetallic contacts or where externally applied potential differences exist. Metallic 'whisker' growth occasionally occurs.

Next, possible effects of corrosion and whisker growth on electrical components are discussed. Failures may result from disconnections due to corrosion of wires, prevention of contact and clogging of moving parts by corrosion products, and from the making of unwanted contacts by metal whiskers, corrosion products and silver migration. A list of corrosion cases is then given, classified according to cause, illustrating some of the corrosion and fault mechanisms. The more interesting cases are commented on briefly. Finally, preventive measures are covered. The ideal environment is provided by a hermetically-sealed enclosure containing a dry uncontaminated inert gas. More practical steps include air purification, adequate ventilation of enclosed equipments, and avoidance of humid conditions and metal-surface contamination.

Bryant, R., M. H. Bester, and J. McCormick. Reliability of microelectronic circuit connections, In: Proc. 1968 Annual Symposium on Reliability, Boston, Mass., Jan. 16-18, 1968, pp. 558-63.

High humidity was found to have an adverse effect on gold-plated Kovar/ribbon.

Campbell, W. E. and R. E. Lee, Jr. Polymer formation on sliding metals in air saturated with organic vapors, ASLE Trans. 5, 91-104 (1962).

A laboratory study of the mechanism of polymer formation, its dependence on metal type and vapor adsorbance.

Campbell, W. E. Atmospheric effects on friction and wear, Machine Design 36 (20), 186+ (1964).

Fundamentals of oxide film formation and gas adsorption.

Campbell, W. E. Factors affecting reliability of electrical contacts for space application, Final Report No. 144, Jet Propulsion Laboratory, Pasadena, Calif., pp. 85-136 (1962).

Review of operating and environmental conditions adversely affecting electrical contact performance.

Campbell, W. E. The tarnishing of silver and copper, In: Proc. Engineering Seminar on Electrical Contacts, Univ. Maine, Orono, Maine, June 14-18, 1965, pp. 343-4.

Sulfide formation reaction mechanisms of silver and copper were investigated.

Campbell, W. E. and U. B. Thomas. Tarnishing and contamination of metals, In: Electrical Contacts, 1968, Proc. Engineering Seminar on Electrical Contact Phenomena, Illinois Institute of Technology, Chicago, Ill., Nov. 11-15, 1968, pp. 233-65.

All of the common contact contaminants were considered, corrosive gases, organic materials, dust, soot, and macroscopic dirt.

Chaikin, S.W. Mechanics of electrical-contact failure caused by surface contamination, Electro-Technol. 68, 70-5 (Aug. 1961).

Contamination from fabrication operations (soldering and welding) and from outgassing of plastic components are difficult to eliminate.

Chaikin, S. W. Study of effects and control of surface contaminants on electrical materials, Final Rept. Proj. PU-3145, Stanford Research Institute, Menlo Park, Calif., June 10, 1961.

This was primarily a study of outgassing and degradation of polymeric materials used in insulation.

Chaikin, S. W. Organic contact deposits under rubbing and non-rubbing conditions, In: Proc. International Research Symposium on Electric Contact Phenomena, Univ. Maine, Orono, Maine, Nov. 1961, pp. 141-58.

Polymer forms on palladium in the presence of hydrocarbon vapors, rapidly with rubbing, slowly without rubbing.

Chaston, J. C. Surface properties: key to contact selection, Mater. Eng. 66, 76-7+ (Aug. 1967).

Gold and platinum alloys are best choices for light duty contacts.

Chiarenzelli, R. V. Analysis of dust obtained from the equipment used in the ASTM two-year exposure test in Newark, General Products Division Development Lab., IBM Corp., Endicott, N.Y., July 1963, 3 pp.

Major components: carbon, ferric chloride; minor components: sulphite, nickel, zinc, and aluminum ions.

Chiarenzelli, R. V. Air pollution effects on contact materials, In: Proc. Engineering Seminar on Electrical Contacts, Univ. Maine, Orono, Maine, June 14-18, 1965, pp. 65-102.

Detailed review of laboratory and field studies with a large amount of contact resistance data.

Chiarenzelli, R. V. and B. C. Henry. Lubricating separable electric contacts and tarnish prevention, Lubrication Eng. 22, 174-80 (May 1966).

Paraffin mixed with polyphenyl ether found to be a good lubricant and corrosion inhibitor.

Chiarenzelli, R. V. and E. L. Joba. The effects of air pollution on electrical contact materials; a field study, J. Air Poll. Cont. Assoc. 16 (3), 123-7 (1966).

Gold, palladium, silver, tin, and lead test pieces were exposed for four months at six industrial sites and contact resistance measurements made.

Chiarenzelli, R. V. Tarnishing studies on contact materials, In: Proc. 3rd International Research Symposium on Electric Contact Phenomena, Univ. Maine, Orono, Maine, June 6-10, 1966, 9 pp.

Laboratory corrosion studies were compared with the earlier field studies.

Chiarenzelli, R. V. Tarnishing studies on contact materials, IEEE Trans. Parts, Mater., Pkg PMP-3 (3), 89-96 (1967).

The contact properties of gold, silver, copper, and nickel were investigated. Corrosion film thicknesses were measured, in addition to contact resistance.

Egan, T. F. and A. Mendizza. Creeping silver sulfide, J. Electrochem. Soc. 107 (4), 353-4 (1960).

Silver sulfide creep through pores in gold plating and across boundaries onto gold contact surfaces was shown to be a serious contact problem.

Egan, T. F. Contamination during manufacture of low energy electrical contacts, In: Electrical Contacts, 1968, Proc. Engineering Seminar on Electrical Contact Phenomena, Illinois Institute of Technology, Chicago, Ill., Nov. 11-15, 1968, pp. 267-8.

Control of contact quality during manufacture is more critical to the electronics industry than the effects of air pollution.

Elsey, H. M., L. E. Moberly and J. L. Johnson. Air humidity and brush contact drop: The effect of water vapor, sulfur dioxide, and hydrogen sulfide, AIEE Trans. Power App. Systems 73, Pt. III-B, 1383-9 (1954).

Carbon brush-copper commutator rings are quite sensitive to humidity. High SO_2 and H_2S concentrations increase film resistance while present.

Ely, C.H.A. and P. J. Lambeth. Artificial-pollution test for high-voltage outdoor insulators, Proc. Inst. Elec. Engrs. 111 (5), 991-9 (1964).

Salt solution fogs were used to set up standard flashover tests.

Ely, C.H.A. and W. J. Roberts. Flashover of polluted h.v. insulators under switching surges, Proc. Inst. Elec. Engrs. 115 (5), 443 (1968).

Extent of contamination was related to voltage surges.

Evans, U. R. Electrical contacts, the effect of atmospheric corrosion, Metal Ind., 10-13 (July 2, 1948).

Study of the corrosion of nickel and copper by sulfur dioxide and hydrogen sulfide.

Evans, U. R. The Corrosion and Oxidation of Metals: Scientific Principles and Practical Applications, St. Martin's Press, Inc. New York, 1960, pp. 481-535.

Chapter XIII. Atmospheric Corrosion Mechanisms of Base Metal Corrosion in Air.

Fairweather, A. The behavior of metallic contacts at low voltages in adverse environments, Proc. Inst. Elec. Engrs. 100 (Pt. 1), 174-82 (1953).

The surfaces of electrical contacts are usually contaminated by foreign layers. Such layers may consist of dust or grease, or of films produced by adsorption, tarnishing or corrosion. The applied voltage is regarded as "low" when it is too small to initiate conduction by any process analogous to breakdown. The problem in such circumstances is to obtain a metal-to-metal contact mechanically. An attempt is made, for the first time, to describe the behavior of a closed contact subjected to corrosion, and the closure processes for a corroded contact, both with and without "wipe."

Fairweather, A. Reliable contacts, In: Electronic Equipment Reliability Symposium, London, 1960, pp. 45-6.

Surface contamination by corrosion or foreign films is the main factor controlling contact behavior.

Fairweather, A., F. Lazenby and A. E. Parker. Long-life low-voltage contacts, Proc. Inst. Elec. Engrs. B-109, Suppl. 22, 567-86 (1962).

The preservation of near-metallic contact, with reasonable contact forces in adverse environments, usually necessitates the use of coatings of precious metals such as gold, platinum, palladium or rhodium. For semi-permanent contacts, the coating requirements are determined almost entirely by considerations of environmental attack. For sliding contacts, considerations of mechanical wear are also involved.

Fairweather, A., R. L. Jury, F. Lazenby, A. E. Parker, D. H. Thrift and L. J. Weight. Massacre, a machine for automatic surface sampling and automatic contact-resistance evaluation, Proc. Inst. Elec. Engrs. A-109, Suppl. 3, 210-19, 228-30 (1962).

The machine described is automatic: ten loads are available and a plate two inches square can be tested at a thousand different places, each observation occupying eight seconds.

The test sequence at each place is as follows. A probe is lowered gently on to the plate, and when stationary, the contact resistance is measured and classified automatically. The probe is then 'wiped' and, again when stationary, a similar evaluation is made. This procedure is repeated for each of seven loads (10, 20, 50, 100, 200, 500 and 1000 g) or until one or other of the two sets of contact resistances falls within a specified range. The remaining three loads can be applied manually when it is necessary to explore a particular load interval in detail.

Fairweather, A. and A. E. Parker. Electrical properties of 'natural' films developed on platinum contacts, Proc. Inst. Elec. Engrs. 113 (4), 581-4 (1966).

First examples of catalytically formed polymer films from hydrocarbon pollution on non-rubbed surfaces.

Fedorov, A. I. and G. Z. Zakirov. Investigation of plug-type connectors operating with microcurrents at microvolts, In: Sotskov, B. S., et al, Electric Contacts, Moscow-Leningrad, 1964, NASA TT F-339, pp. 223-33. (in Eng.).

In the microvolt signal range, electric contacts may become unstable due to the appearance of momentary contact potentials.

Flatau, G. Reliable contacts and connections in telecommunication plant, Inst. Elec. Engrs. Trans. (Australis) EE-3 (1), 59-67 (Mar. 1967).

A general paper reviewing physical factors controlling contact behavior and the major effects tending to degrade contact behavior.

Forrest, J.S., P. J. Lambeth and D. F. Oakeshott. Research on the performance of high-voltage insulators in polluted atmospheres, Proc. Inst. Elec. Engrs. A-107, 172-96 (1960).

A review of the contamination flashover problem.

Forster, D. L. and B. G. Gebauer. Factors in choosing electrical contacts, Autom. Elec. Tech. J. 9 (7), 252-9 (1965).

Circuit characteristics and environment must be considered in choosing optimum contacts.

Frant, M. S. Copper sulfide creep on porous electroplate, J. Electrochem. Soc. 107 (12), 1009-11 (1960).

Silver sulfide creeps over gold, copper sulfide creeps over gold, palladium, nickel and tin, and this phenomenon must be considered in selecting contacts.

Frant, M. S. Connectors and galvanic corrosion, Electron. Ind. 20, 112-16 (Dec. 1961).

Aluminum is most susceptible to galvanic corrosion when coupled with any other metal except tin.

Freudiger, E. Investigation of surface contamination on fine silver contacts, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1960, pp. 45-51.

The concern here was primarily with dirt and contaminants introduced at time of fabrication.

Freudiger, E. Electrical contact materials, properties and selection, Electro-Technol. 69, 72-8 (June 1962).

A study of factors influencing contact resistance and contact degradation.

Fujitaka, S., T. Kawamura, S. Tsurumi, H. Kondo, T. Seta and M. Yamamoto. Japanese method of artificial pollution tests on insulators, IEEE Trans. Power App. Systems PAS-87 (3), 729-35 (1968).

Describes flashover test developed in Japan involving controlled spraying of salt solutions of known concentration.

Gaiennie, D. E. Clean insulators with washer 'gun', Elec. World 153, 87 (Mar. 28, 1960).

A truck mounted gun, with 700 psi pump was used to wash insulators during normal power transmission operation.

Germer, L. H. and J. L. Smith. Activation of electrical contacts by organic vapors, Bell System Tech. J. 36, 769-812 (May 1957).

This paper defines and describes "activation" of platinum metal contacts.

Germer, L. H. and J. L. Smith. Organic vapor and relay contacts, Bell Lab. Record 36, 122-6 (April 1958).

Erosion from contact activation is hermetically sealed relay problem.

Glossbrenner, E. W. Sliding precious metal contacts and electrical noise, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1959, pp. 24-30.

The factors controlling electrical noise level in these devices was discussed.

Gothberg, A. W., A. R. Koerber and C. E. Zanzie. Contamination testing of arresters for 500-kV systems, IEEE Trans. Power App. Systems PAS-87 (3), 703-12 (1968).

Contamination flashover problems become more severe as transmission voltages increase.

Halstrøm, H. L. Tarnishing of silver and silver-silicon contacts by hydrogen sulfide, J. Inst. Metals 5, 144 (1961).

Simple passification of silver surfaces is claimed by oil treatment, mild soap washing and water rinsing.

Hampton, B. F. Flashover mechanism of polluted insulation, Proc. Inst. Elec. Engrs. 111 (5), 985-90 (1964).

The voltage gradient of an arc burning in steam is higher than the voltage gradient of an arc burning in air.

Hara, T. and K. Mano. Thermodynamical studies on the dry corrosion of several contact materials, Tech. Rept 19, Research Institute of Electrical Communication, Tohoku Univ., Sendai, Japan, 1967, 28 pp.

Oxidation and sulfurization functions were developed for several metal and alloy contact materials.

Harding, W. B. The tarnish resistance of gold plating over silver, Plating 47, 1141-5 (Oct. 1960).

Problem of silver sulfide creep through gold plate pores is explored.

Harris, H. R. Four measures minimize an unusual case of insulator contamination, Elec. World 142, 80-3 (July 26, 1954).

Four measures for combating atmospheric contamination of insulators:

1. Provision of ample insulator surface leakage length
2. Periodic silicone coating of insulator surfaces
3. Periodic washing
4. Reduction of contaminants in the atmosphere through cooperation with a neighboring plant.

At least one of these, the application of silicone coating, is believed to be new to the industry.

Hermance, H. W. and T. F. Egan. "Fingerprinting" relays, Bell Lab. Record 34 (8), 289-93 (1950).

Plastic replico techniques were used to examine contacts and identify contaminants.

Hermance, H. W. and T. F. Egan. Organic deposits on precious metal contacts, Bell System Tech. J. 37 (3), 739-76 (1958).

An amorphous brownish organic deposit was found on non-arcing palladium contacts. It was shown that this material is produced when a number of metals, notably those of the palladium and platinum groups, are rubbed together in the presence of low concentrations of organic vapors. The deposit is given by a very wide variety of organic materials, and first involves chemisorption of the vapor on the metal, followed by frictional activation and polymerization of the chemisorbed layers to form the visible accumulation. The use of a gold alloy overlay on the palladium tends to minimize the growth of the polymer on the contact surface.

Hermance, H. W. Combatting the effects of smog on wire-spring relays, Bell Lab. Record 44 (2), 48-52 (1966).

Dust in Los Angeles, high in ammonium nitrate content, was found to cause stress corrosion in the wire springs used in telephone relays. Countermeasures included use of high efficiency filters on existing installations and change of wire spring alloy to one unaffected.

Hill, G. L. Tests and developments in connection with hot-line insulator washing. AIEE Trans. 66, 1203-16 (1947).

High pressure water and high pressure steam washing methods were investigated.

Holm, R. and E. Holm. Electric Contacts, Theory and Application, Springer-Verlag, Inc., New York, 1967.

Standard definitive reference book for electric contacts.

Hosokawa, Y. Abnormal contact erosion of switching relay, NEC Res. Develop., Nos. 4/5, 10-24 (1963).

The contacts of wire spring relays were found abnormally eroded at "F" central, only after one year and a half of use. The investigation into the cause of this erosion was carried out at the central and in the laboratory. The results showed that the cause of abnormal erosion of contact is the activation of contact due to the aromatic hydrocarbon vapor of oily TT wax used for floor polishing and that the further erosion was stopped by using active carbon filters.

Hyde, N. Electromechanical relays. Part 3. The contact problem, Electron. Compon. 5 (8), 665-9 (1964).

Factors affecting relay performance are discussed.

Hyde, N. Electromechanical relays. Part 4. Reliability testing, Electron. Compon. 5 (10), 865-72 (1964).

General treatment of testing procedures and instrumentation.

Ignacz, P. Silicone-greasing provides excellent insulator flashover protection, Power Eng., 56-7 (Oct. 1962).

Kaufman, J. W., H. R. Sutton, A. V. Balchaitis and W. R. Matthias. Dry-circuit evaluation of mechanical connections, Elec. Manuf. 65 (4), 116-21 (1960).

A summary of the causes of non-conduction in low-level electrical contacts and the results of environmental tests on two forms of mechanical-type connectors evaluated from a reliability standpoint in dry circuits encountered in defense electronic equipment.

Kawai, M. Tests in Japan on the performance of salt-contaminated insulators in natural and artificial humid conditions, Proc. Inst. Elec. Engrs. 115 (1), 158-68 (1968).

Describes work done in experimental studies to identify the mechanism of contamination flashover.

Keefer, H. J. Dust on relay contacts, Bell Lab Record 35, 25-8 (1957).

Dust destroys contact reliability. Air filters are an absolute necessity.

Keil, A. G. Some materials problems in electrical contacts, Mater. Res. Std. 3 (6), 489-91 (1963).

A discussion of silver sulfide creep, contact deformation by arcing and the resistivity of foreign films.

Keller, A. C. Recent developments in Bell System relays - particularly sealed contact and miniature relays, Bell System Tech. J. 43 (1), 15-44 (1964).

Important developments are miniaturization, sealed contact relays using glass-enclosed contacts, and "remanent" type devices. Ferreed and bipolar ferreed coordinate arrays and individual units are new and important switching elements. These devices make use of miniature glass-enclosed contacts in combination with "square loop" magnetic material such as ferrite or certain iron alloys. They are magnetic "latching" units and are operated or released by short pulses.

King, J. High pressure electrical contacts, In: Proc. 1968 Electronic Components Conference, May 8-10, 1968, pp. 454-8.

Satisfactory performance has been achieved with high pressure contacts of uncoated base metals. These contacts were neither protected from, nor deliberately exposed to contamination. Variations of both point and line contact configurations have been evaluated and their performance falls into predictable patterns. Sufficient test data has been evaluated and the following conclusions can be drawn: (1) tarnish films on base metal are penetrable by high pressure contact indentors without resorting to a wipe motion; (2) line contact chisels and point contact cones with large included angles are superior to thin knife-like or needle-like contacts; (3) relative contact hardness is important in that both indentor and flat contact target must deform to expose base metal or the resulting interface will consist of one contact with bare metal exposed and in direct contact with the insulating tarnished surface of the other contact.

Krumbein, S. J. and M. Antler. Inhibition of corrosion and wear of gold plated contacts, Res. Rept. 51, Res. Div., Burndy Corp., Norwalk, Conn., Jan. 26, 1967, 20 pp.

The increasing reliability requirements for low voltage electric contacts has led to a search for methods which could make gold plated surfaces impervious to the effects of atmospheric pollutants. The susceptibility of thin gold plate to corrosion is due both to its inherent porosity and its removal by wear. Because of these breaks in the plate, pollutants can attack the substrate metal or underplate to produce insulating corrosion products.

The best methods were the application of a pore blocking inhibitor and a lubricant coating having a liquid component. They inhibited corrosion and wear effectively, without significantly increasing contact resistance compared to untreated samples. These methods were superior to solid lubricant coatings that have been previously proposed.

Lambeth, P. J. Preventing pollution flashovers, Elec. Rev. 174, 662-6 (1964).

A survey of methods in use or being developed to eliminate pollution flashovers.

Lambeth, P. J., J. S. T. Looms, A. Stalewski and W. G. Todd. Surface coatings for h.v. insulators in polluted areas, Proc. Inst. Elec. Engrs. 113 (5), 861-9 (1966).

Petroleum jelly and silicone grease are both effective, but expensive inhibitors of contamination flashover.

Larrabee, C. P. and O. B. Ellis. Corrosiveness of various atmospheres, Mater. Res. Std. 1, 977 (Dec. 1961).

ASTM report on the relative corrosiveness of the atmosphere at 37 locations in the U.S. with regard to steel and zinc.

Last, F. H., T. H. Pegg, N. Sellers, A. Stalewski and E. B. Whittaker. Live washing of h.v. insulators in polluted areas, Proc. Inst. Elec. Engrs. 113 (5), 847-60 (1966).

A review of the effectiveness on live or "hot" washing of h.v. insulators with high pressure water to prevent contamination flashover.

Lilienfeld, S. and C. E. White. A study of the reaction between hydrogen sulfide and silver, J. Am. Chem. Soc. 52, 885-92 (1930).

This paper shows that dry H_2S will not attack silver but if oxygen is added to the dry system silver sulfide is formed.

Lish, E. F. Identification of contact contamination, In: Electrical Contacts, 1960, Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1960, pp. 38-43.

Contact contamination has several potential sources. All of the fabrication assembly and cleaning operations can inadvertently add contaminants.

Lodge, J. P., Jr. and B. R. Havlik. Evaporated metal films as indicators of atmospheric pollution, Intern. J. Air Pollution 3 (4), 249-52 (1960).

Glass slides covered with films of aluminum, iron, lead, copper and silver were prepared and exposed in the Cincinnati area to measure atmospheric corrosiveness.

Corrosion products were identified by means of X-ray diffraction and microchemical methods. Corrosion results in an increase in light transmission by the film, which can be taken as a quantitative measure of corrosion. Preliminary results showed aluminum to be the most dependable indicator of general atmospheric corrosiveness, although silver appeared specifically sensitive to a small group of pollutants, such as halogens, ozone, and sulfur compounds. Lead corroded so rapidly as to be difficult to interpret while iron was shown to be responsive primarily to relative humidity. Fair correlations were obtained with independent measures of pollution level. Some exploratory work was done on the measurement of the electrical resistance of the films.

Lodge, J. P., Jr. and E. R. Frank. Evaporated metal films as indicators of atmospheric pollution. II. Resistance measurements, Intern. J. Air Water Pollution 6, 215-21 (1962).

A technique was developed relating corrosive pollution level to contact resistance.

Maddock, A. J., C. C. Fielding, J. H. Batchelor and A. H. Jiggins. The effects of dust and force upon certain very light electrical contacts, Brit. J. Appl. Phys. 8, 471-80 (1957).

Dust was found to cause high contact resistance at very low force loadings.

Mader, W. M. Organic free slip ring assemblies - possibility or reality? Marshall Space Flight Center, Huntsville, Ala., 1966.

Whenever organic material is enclosed in slip ring assemblies, there is a danger of polymer film formation on contact surfaces before the part is put into operation. This can cause immediate failure when an attempt is made to use the assembly.

Mahler, P. The effects of contamination on relay performance, In: Electrical Contacts, 1960, Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 1960, pp. 64-6.

The kinds of contaminants were listed - oil, rosin, detergent, organic vapors, and moisture, and their actions on contact surfaces outlined.

McKinney, N. and H. W. Hermance. Stress corrosion cracking rates of a nickel-brass alloy under applied potential, Stress Corrosion Testing, ASTM STP 425, Am. Soc. Testing Mater., 1967, pp. 274-91.

A method was developed to test the susceptibility of nickel-brass alloys to stress corrosion cracking in the presence of nitrates or other salts. A wire of the alloy under test was stressed, and an electrical leakage path was provided to a cathode by the electrolyte being studied. Stresses, potentials, salt concentrations, relative humidities, and time were varied to evaluate these factors.

McManus, J. J. Improving contact reliability in low-level circuits, Electro-Technol. 69, 98-101 (May 1962).

Super imposing a 120 v "wetting voltage" signal across low-level contacts as a means of assuring contact reliability is proposed.

Moberly, L. E. Atmospheric effects on sliding contacts, In: Proc. Engineering Seminar on Electrical Contacts, Pennsylvania State Univ., Univ. Park, Pa., June 25-29, 1956, 19 pp.

The effects of moisture, H_2S, SO_2, hydrocarbon vapor, and silicone vapor on sliding contacts were discussed.

New, A. A. An analysis of failure of components, Radio Electron. Components 1, 193-201 (Feb. 1960).

A detailed examination of the factors causing component failure.

Phillips, V. A. Role of defects in evaporated silver films on the nucleation of sulfide "patches", J. Appl. Phys. 33 (2), 712-17 (1962).

Studied by transmission electron microscopy: Defect sites were attack points of H_2S.

Pitney, K. E. The ASTM method of test for microcontacts, In: Electrical Contacts, 1965, Proc. Engineering Seminar on Electrical Contacts, Univ. Maine, Orono, Maine, June 14-18, 1965, pp. 293-311.

Use of the ASTM microcontact resistance tester is described.

Rance, V. E. and H. G. Cole. Corrosion of metals by vapours from organic materials, Inter-service Metallurgical Research Council, Her Majesty's Stationery Office, London, 1958, 25 pp.

A number of metals were enclosed with various plastics and resins for long test periods, then examined for corrosion damage.

Ridker, R. G. Economic costs of air pollution studies in measurement, Frederick A. Praeger, 1967, pp. 66-71.

Shtremberg, T. K. and D. V. Gayevskaya. Special features of switching low level currents and voltages by means of contacts, In: Sotskov, B.S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT-F-339, pp. 276-300. (in Eng.).

Technically, pure gold is recommended as the only satisfactory contact surface for low level contacts.

Snowball, R. F., J. B. P. Williamson and R. C. Hack. Ingress-limited corrosion of contacting surfaces, IEEE Trans. Parts, Mater., Pkg. *PMP-3* (3), 82-4 (1967).

The most pressing problem in electric contact testing is to define the modes by which contacts fail. Until we understand why and by what mechanism contact spots stop passing electricity between the mating members, it will be impossible to devise relevant life-testing procedures. This paper describes an experimental technique whereby interfaces can be observed during exposure to moist, polluted air and the degradation of contact spots studied *in situ*. The reactions that occur are analyzed in terms of the physical effects of the ingress of reactants into contact joints, and the resistance changes observed. The distinction between ingress-limited corrosion and reaction-limited corrosion is introduced, and the death of contact spots is observed under the microscope. This technique makes possible the direct observation of the progressive corrosion of an array of contact spots, and reveals in detail how the conducting area of each spot is eroded by the chemical action.

Solov'yeva, S. F., I. I. Sigachev, N. A. Surkova and Ye. V. Kogteva. Contacts of relay-type elements and microswitches which commutate low level signals, In: Sotskov, B. S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT F-339, pp. 301-31. (in Eng.).

A review of the requirements of low level contacts for satisfactory performance.

Spelman, J. W. Where rhenium is growing, Metal Progr. *93* (2), 103-4+ (1968).

The chemical and physical properties of rhenium make the metal well suited for many electrical contact applications.

Tripp, J. H. and J. B. P. Williamson. A model of mechanical breakup of films on conductors, In: Proc. 3rd International Research Symposium on Electric Contact Phenomena, Univ. Maine, Orono, Maine, June 1966, pp. 71-8. (in Ger.).

Film breakdown is one of the ways to combat air pollution effects on electrical contacts.

Turner, H. W. and C. Turner. Contact materials, their properties and uses, Pt. 2, Elec. Times 152 (8), 277-81 (1967).

A description of aluminum, copper, silver, nickel, tungsten, molybdenum, and rhenium as contact materials.

Ulsh, H. B. Current ideas in the philosophy of testing electrical contacts, IEEE Intern. Conv. Record 14 (9), 35-8 (1966).

Environmental test procedures are described.

Van Auken, R. L., W. D. Hensley and S. R. Cole. Totally inorganic assemblies, an approach to contamination free sliding contacts, In: Electrical Contacts, 1967, Proc. of the Engineering Seminar on Electric Contact Phenomena, Illinois Institute of Technology, Chicago, Ill., Nov. 6-9, 1967, pp. 119-23.

This approach eliminates organic polymer films.

Wagner, R. J., A. E. Sprando, and J. R. Laskie. Reduction of contact contamination with activated carbon getters, In: 9th National Conference on Electromagnetic Relays, Natl. Assoc. Relay Manufacturers, Oklahoma Institute of Technology, Stillwater, Okla., 1961, pp. 35-8..

This is probably not as satisfactory as organic-free assemblies.

Williamson, J. B. P., J. A. Greenwood and J. Harris. The influence of dust particles on the contact of solids, Proc. Royal Soc. A-237 560-73 (1956).

Shows dust to be detrimental to electrical contact operation.

Williamson, J. B. P. Recent studies on the physics of electrical connector surfaces, IEEE Trans.Parts, Mater., Pkg. PMP-2 (3), 71-5 (1966).

The manner in which two conductors touch to form an electrical contact is described, and the influence of the phenomena occurring at the interface on the engineering properties of the connector is discussed. In the last ten years, significant advances have been made in our knowledge of the mechanical, electrical, and thermal aspects of the contact between surfaces. These have led to a better understanding of the deterioration processes which occur naturally in connectors. A new philosophy of the evaluation and specification of connectors which utilizes these results and which links the engineering reliability of the device to the basic science of the interface is discussed.

Wohlers, H. C. Corrosion aspects of air pollution in the San Francisco Bay area - Electrical contact points, Internal Rept. BAAPCD, 1964 5 pp.

Part of a general assessment of the economic effects of air pollution in the Bay Area.

APPENDIX B

PERSONAL CONTACTS

A. Industrial Visits

These visits were made during the period July 1968 to March 1969.

AMP INC.
Research and Development Laboratory
Harrisburg, Pa.

Talked with: Mr. Ryle, Laboratory Manager
Mr. J. H. Whitley

AMP manufactures mating connectors, terminals, pin and socket connectors, card reader contacts, and connector assemblies. High current connectors have no air pollution problems. Low current, low voltage contacts are gold plated to minimize effects of air pollution and other deleterious environmental factors. AMP spends about $2,000,000 for gold.

Air conditioning costs in a computer installation amount to about 8% of the total installation costs.

Air pollution effects (particulate fallout) will become more serious in ultra high voltage power transmission as voltages increase. Working voltages of 765 KV or higher are expected soon. Effects are contamination flash-over, radio interference from corona flumes, and current losses from corona.

ASSOCIATED SPRING CORPORATION
Barnes Wallace Division
100 Wallace
Bristol, Connecticut

Talked with: Mr. Phillip Lombary, Engineer
Mr. James Maker, Chief Metallurgist

Discussed use of gold plating for dry circuits and other ways of contamination prevention.

BELL LABORATORIES
Holmdel, New Jersey

Talked with: Mr. Thomas Egan

While the electrical contacts in telephone systems are not as susceptible to air pollution effects as electrical contacts in some other lower voltage systems, such as computers, because the telephone network is so vast and the expected service life of the relay and switching components is so great, air pollution effects are of serious concern. A minimum of 20 years service life is demanded for the electrical contacts in the system, regardless of operating conditions or environment.

Bell Telephone prefers palladium to gold in their telephone relays because the wear properties of palladium in electrical contacts are far superior to the wear properties of gold. However, the use of palladium introduces another air pollution type problem, i.e., the formation of build-up of frictional polymer. If organic vapors are present where palladium plated contacts are in service, these vapors are catalytically polymerized by the palladium and a brown deposit of polymer grows on the contact surface. This brown deposit can cause open circuit failure in telephone switching by building a thick insulating layer.

The specific problem of silver migration in electrical insulation was briefly discussed. This effect is primarily dependent upon humidity and thus is not closely related to air pollution effects on electrical contacts.

Contact activation caused by carbon residues from organic contaminants on electrical contacts used in medium and heavy duty relays and switches is nearly always a result of air pollution. This condition is undesirable because it brings on accelerated arc erosion on the contact surface. Platinum metal contacts are especially susceptible to contact activation from carbonization of frictional polymer, which will form if organic vapors are present.

BURNDY CORPORATION
Norwalk, Connecticut

Talked with: Dr. Morton Antler, Deputy Director
Research Division

Burndy is one of the large manufacturers of electrical contacts. Most of the microcontacts produced by Burndy are gold-plated and the company, through its research division, has done much valuable research on the precious metal plating of electrical contacts.

High reliability contacts can be produced with a minimum of gold plate by using smooth substrates and nonporous underplates chosen to minimize substrate diffusion through the gold plate.

In the Burndy laboratory at the present time there is the feeling that gold plate could be eliminated in the manufacture of electrical contacts should the proper corrosion-inhibiting system be developed for base metal contacts.

RENSSELAER POLYTECHNIC INSTITUTE
Troy, New York

Talked with: Dr. Wilfred E. Campbell, Consultant

Problems related to acceleration of contact erosion by organic vapors; corrosive effects of particulate films on contacts; the mechanisms of silver tarnish; and the general roles of gaseous and particulate pollutants in contact failure were discussed in detail. Dr. Campbell cited examples of secondary wear effects of contact exposure to pollutants, both deleterious and beneficial.

DREXEL INSTITUTE OF TECHNOLOGY
Philadelphia, Pennsylvania

Talked with: Dr. Henry Wohlers, Associate Professor
Environmental Sciences Division

Discussed differences in materials damage among urban air sheds, specifically differences in metalic corrosion.

ENGELHARD INDUSTRIES
Mallory Division
Newark, New Jersey

Talked with: Dr. Victor G. Mooradian

The Mallory Division of Engelhard Industries makes precious metal alloys for industry. They have 500 alloy compositions for electrical contact application; of these 100 are regularly used. Two hundred of these alloys contain silver as a major component.

Sulfiding of silver containing electrical contacts can be inhibited in a number of ways. As much as 25% silver in a gold-silver alloy retains a sulfur corrosion resistance comparable to that of pure gold. Another corrosion resistant system is made up of gold diffused on silver. It is claimed that this combination can be used with as much as 75% silver. Small amounts of mercury (2 to 3%) diffused into silver reduce the tendency for a silver contact surface to tarnish.

About 10 to 20% of the business of Mallory Division of Engelhard Industries is based on requirements to eliminate air pollution effects on electrical contacts.

GENERAL ELECTRIC COMPANY
Pittsfield, Massachusetts

Talked with: Mr. M. Kawai, Research Engineer
Project UHV Facility

Certain types of contamination flashover of high voltage transmission lines are caused by particulate pollution although a large fraction of such flashovers are caused by natural particulate accumulations. One specific pollutant material,which is particularly troublesome, is calcium chloride in areas where it is used to de-ice highways. Fallout from industrial stacks can also cause problems in local areas.

GENERAL ELECTRIC COMPANY
High Voltage Laboratory
Philadelphia, Pennsylvania

Talked with: Mr. Wendell Starr
Mr. H. O. Schneider
Mr. Roy Anderson

We discussed the problem of the effect of particulate pollution on high voltage flashover in transmission lines as related to the magnitude of the line voltage. Problems are severe at ultra high voltages (750 to 1000 KV).

HARVEY HUBBELL, INC.
Bridgeport, Connecticut

Talked with: Mr. R. M. Murphy, Vice President
Mr. E. R. Carlson, Manager
Advance Design and Development

Hubbell manufactures cold formed parts for electrical contact assemblies. Many of their contacts are manufactured from beryllium, copper, nickel, brass, or bronze, but they will process precious metal plate parts on a custom basis. Their customers have reported no problems attributable to air pollution and their feeling is that corrosion problems are specific and local.

IBM
Durham, North Carolina

Talked with: Dr. D. M. Preiss, Manager
Materials Laboratory

IBM is interested in attaining essentially perfect performance of their gold-plated connector boards for a period of at least five years and they would also like to see an accelerated test method that would accurately foretell the performance characteristics of electrical contact systems. At present, they use the cycling temperature and humidity test, the flowers of sulfur test, and the salt spray test for accelerating corrosion.

ITT CANNON ELECTRIC
Los Angeles, California

Talked with: Mr. Warren Keating

ITT Cannon Electric manufactures switches, relays, and contact assemblies for commercial and communications applications.

A generally used approach to improving contact reliability is increasing the thickness of the gold plate; but where soldered connections to gold plated contacts are made, the tendency to form a brittle gold-solder eutectic increases with thickness of the gold plate. Therefore, recent developments have led toward the use of thinner gold plate on smoother substrates. The gold plate porosity can be reduced dramatically by careful substrate surface preparation.

J. M. NEY AND CO.
Bloomfield, Connecticut

Talked with: Mr. K. E. Pitney, Manager
Electronic Research and Development

The Ney Co. makes contact parts for encoders, potentiometers, gyros, tape and card readers, and many specialized applications. Most of their contacts are solid precious metal alloys bonded to rigid plastic support. The metal is one to three mil thick and the alloy formulations are generally so nonreactive that air pollution has no effect on contact performance.

LITTON PRECISION PRODUCTS, INC.
Poly-Scientific Division
Blacksburg, Virginia

Talked with: Mr. Wesley Mader, Vice President-Engineering

This Company makes guidance systems for missiles, launch-stage space vehicles, ships, and aircraft. Very important components of these systems are the various integral slip ring assemblies. These assemblies represent one important type of low load electrical contact. Other high reliability electrical contact assemblies are also produced.

These components or units are invariably sealed. They are fabricated by the best procedures known, of the best available materials. The cost of making these components is justified because they are used in such critical applications in such valuable and important systems.

Their one unresolved reliability problem concerns potential electrical contact failure due to internal environment contaminants, such as solar flux or polymer produced catalytically from organic vapors. These organic vapors are the result of outgassing of insulation or other organic components in the assembly.

B. Telephone Contacts

These telephone contacts were made during the period July 1968 to August 1969.

AUTO SWAGE PRODUCTS
Shelton, Connecticut

Talked with: Mr. Robert Burns, Chief Engineer

No air pollution problems recognized, yet they do use gold plate connectors to order.

IBM
Poughkeepsie, New York

Talked with: Dr. Robert V. Chiarengelli, Research Engineer

Discussed environmental chamber tests for contact materials and the advantages and limitations of the flowers of sulfur test.

ITT GENERAL CONTROLS
Glendale, California

Talked with: Mr. J. Robert Brown, Director of Research

Mr. Brown felt air pollution has no effect on power relays and switches.

MICRODOT, INC.
South Pasadena, California

Talked with: Mr. W. Doherty, Engineer

Discussed required cleanliness for contact manufacture.

PACIFIC GAS AND ELECTRIC COMPANY
San Francisco, California

Talked with: Mr. Richard H. Brainard, Staff Engineer

Discussed contamination flashover in the Bay Area.

PACIFIC TELEPHONE AND TELEGRAPH COMPANY
Los Angeles, California

Talked with: Mr. N. G. Reetz, Staff Engineer

Discussed the pollution problems unique to the Los Angeles area, including frictional polymer formation on palladium contacts and the corrosive nature of ammonium nitrate.

SOUTHERN CALIFORNIA EDISON POWER COMPANY
Los Angeles, California

Talked with: Mr. W. E. Schroder, Staff Engineer

Discussed the contamination flashover problem and the cost of preventive measures taken by Southern California Edison Company (hot washing).

STANFORD APPLIED ENGINEERING
Santa Clara, California

Talked with: Mr. Daniel Munson, Engineer

General discussion of electrical contact contamination.

APPENDIX C

GENERAL ELECTRICAL CONTACT AND CONTAMINATION FLASHOVER BIBLIOGRAPHY

GENERAL ELECTRICAL CONTACT AND CONTAMINATION FLASHOVER BIBLIOGRAPHY

Abbott, William H., "The Mechanism of Tarnishing of Silver and Copper," Electrical Contacts, 1968, Proc. Engineering Seminar on Electrical Contact Phenomena, Ill. Institute Technol., Chicago, Ill., Nov. 11-15, 1968, pp. 53-4.

Adkins, R. M., "Dry Circuit Contacts and the Applicable Theoretical Phenomena," Proc. International Research Symp. on Elect. Contact Phenomena, Univ. Maine, Orono, Nov. 1961, pp. 121-38.

Adolfsen, G., "Maintenance of Protective Relays at Fairless Works," Iron and Steel Engineer, Vol. 40, Sept. 1963, pp. 93-8.

Anderson, Jack R., "Research and Development Work Relating to Cable Connecting Networks for Micro-Modular Equipment," Stanford Research Institute project prepared for U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey (Contract No. DA-36-039-SC-85275, Technical Requirements No. SCL-7515, dated 9 April 1959), Report No. 12, Final Report, February 15, 1960 to July 1, 1961.

Anderson, Jack R., "Stable Sliding Connector Contacts," SRI PMU3915, Contract No.DA36-039-SC-89150, Final Report, Dec. 1, 1961 to Sept. 30, 1963, 57pp.

Ando, Hideo, "Prevention of Tarnishing of Silver," Japanese patent 4001 ('51), July 25.

Angus, H. C., "Properties and Behaviour of Precious-Metal Electrodeposits for Electrical Contacts," Trans. Inst. Metal., 39 1962, pp. 20-28.

Antler, Morton, "Organometallics in Lubrication," Ind. Eng. Chem., Vol.51, No. 6, June 1959, pp. 753-8.

Antler, Morton, "Contact Properties of Tarnish and Corrosion Films on Metal Foils Exposed at ASTM Newark, New Jersey Site," Memorandum to Members, ASTM Committee B-4 Sub-Committee IV, Nov. 16, 1962.

Antler, Morton, "Multifunctional Oil Additives," U.S. patent 3,063,943, Nov. 13, 1962.

Antler, Morton, "Metal Transfer and the Wedge Forming Mechanism," J. Applied Physics, 34(2), 1963, pp. 438-9.

Antler, Morton, "Lubricant Compositions," U.S. patent 3,077,451, Feb. 12, 1963.

Antler, Morton, "The Lubrication of Gold," Wear, 6 (1963), pp. 44-65.

Antler, Morton, "New Developments in the Surface Science of Electric Contacts," Plating 53(12), 1966, pp. 1431-9.

Antler, Morton, "Processes of Metal Transfer and Wear," Wear, 7, 1964, pp. 181-203.

Antler, Morton, "Current Topics in the Surface Chemistry of Electric Contacts," IEEE Transactions on Parts, Materials and Packaging, Vol. PMP-2, No. 3, Sept. 1966, pp. 59-67.

Antler, Morton and J. B. P. Williamson, "Role of Topography in Electronic Contacts," 8th Intern. Electronic Circuit Pkg. Symp. 8, 1967, pp. 1-10.

Aronstein, Jesse, "Separable Contacts for Semiconductor Chips," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 243-60.

Atalla, M. M., "Arcing of Electrical Contacts in Telephone Switching Circuits, Part II - Characteristics of the Short Arc," Bell Syst. Tech. J. 32(6), 1953, 1493-1506.

Axelson, J. S. and F. M. Precopio, "A Reliable Technique for Measuring Brush Wear in an Atmosphere Containing Silicone Vapor," ASTM Bull., Feb. 1960, pp. 40-2.

Baker, Richard G., "Coatings for Contact Surfaces," Reliable Electrical Connections, 1958, Third EIA Conf. on Reliable Electrical Connections, Dallas, Texas, Dec. 2, 3, 4, 1958, pp. 219-30.

Baker, R. G., C. A. Holden and A. Mendizza, "Porosity in Electroplated Coatings - A Review of the Art with Respect to Porosity Testing," American Electroplater's Society. Report of Proceedings, Vol. 50, 1961, pp. 61-67.

Ball, I. D. L. and R. G. J. Butler, "High Stability Carbon-Film Fixed Resistors," Electrical Research Association Confidential Tech. Report Z/T124, 1959.

Barkan, P. and E. J. Tuohy, "A Contact Resistance Theory for Rough Hemispherical Silver Contacts in Air and in Vacuum," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-84, No. 12, Dec. 1965.

Bartoň, K., "Protection of Metals Against the Atmospheric Corrosion in the Tropics," Slaboproudy Obzor, Vol. 20, No. 8, 509-14 (1959). In Czech.

Bartoňová, N., "Surface Protection of Printed Circuits," Slaboproudy Obzor, Vol. 21, No. 9, 547-9 (1960). In Czech.

Beattie, R. W., G. Forshaw, and E. N. Leney, "Design, Material and Performance of Plugs and Sockets for Electronic Switching Applications," Proc. IEEB, 109, Suppl. 21-22, 102-110 (1962).

Beattie, R. W., "Discussion on Electro-Mechanical Devices (Relays, Plugs, Sockets, etc.) at the Conference, 13th June, 1961," Proc. IEEB 109, Suppl. 21-22, 122-6 (1962).

Bedetti, F. V. and R. V. Chiarenzelli, "Porosity Testing of Electroplated Gold in Gelled Media," Plating 53(3), 305-8 (1966).

Beeck, Otto, J. W. Givens and E. C. Williams, "On the Mechanism of Boundary Lubrication. II. Wear Prevention by Addition Agents," Royal Soc. Proc. A177, 103-9 (1940).

Berberich, L. J., "Deteriorating Influences on Dielectric Materials," Elect. Manufacturing 54, 103-7 (July 1954).

Berger, W. M., R. S. Keen, G. L. Schnable, "Reliability Phenomena in Aluminum Metalizations on Silicon Dioxide," Symp. on Phys. of Failure in Electronics, RADC, 4, 1-31 (1966).

Beyer, M. and H. Langer, "The Effect of Water on the Dielectric Properties of Epoxy Moulding Materials," Elektrotech, Z. (ETZ) A (Germany), Vol. 88, No. 23, 569-73 (10 Nov. 1967). In German.

Biestek, Tadeusz, "The Comparative Corrosion Tests of Passivated Silver Electrodeposits," Natl. Assoc. Corrosion Eng., Ext. Abstr., 1962, pp. 96-7.

Billings, M. J. and K. W. Humphreys, "Results of Outdoor Ageing of Cast Epoxide Systems Under Electrical Stress," Proceedings Seventh Electrical Insulation Conference, Chicago, 1967 (New York: Institute of Electrical and Electronic Engineers, Inc., 1967) pp. 213-17.

Binder, Kurt, "Beitrag zur Dynamik des Kontakts Kohlebürste - Lamelle," (A Contribution to the Dynamics of the Carbon Brush/Lamination Contact), Elektrotechnische Zeitschrift (ETZ) A 82 (2), 46-53 (Jan.1961).

Blake, Bruce E. and George D. Fatzer, "A Preliminary Wear Study of Gold Plated Contacts," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1959, pp. 39-54.

Blake, B. E., "Summary Report of the ASTM Section G Contact Field Tests," ASTM Committee B4, Sub-Committee IV, 14 pages.

Blech, Ilan A. and Harry Sello, "Some New Aspects of Gold-Aluminum Bonds," Journal of the Electrochemical Society, 113, 1052-4 (October 1966).

Blue, M. D., N. W. Willmore, and A. G. Bezat, "Noise and Wear in Wire-Wound Potentiometers," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1960, pp. 93-106.

Bodamer, A., "Modern Relays Satisfy Exacting Electrical and Mechanical Requirements," Electronica (Netherlands), Vol. 19, 321-4 (13 May 1966). In Dutch.

Boehme, H. and F. Obenaus, "Pollution Flashover Tests on Insulators in the Laboratory and in Systems and the Model Concept of Creepage-Path Flashover," Conférence Internationale des Grands Réseaux Électriques Paris, 1966 (Paris: Conférence Internationale des Grands Réseaux Électriques, 1966) Paper No. 407.

Bol'shakov, M. G., "Multibank Rotary Selector Switches PMP," Priborostroenie (USSR), 1966, No. 5, 22-4 (May). In Russian. English translation in: Instrum. Constr. (GB), 1966, No. 5, 26-8 (May).

Booker, C. J. L. and J. L. Wood, "Further Electrical Effects of the Adsorption of Water Vapour by Anodized Aluminium," Proc. Phys. Soc. LXXVI, 5, pp. 721-31.

Bowden, F. P. and D. Tabor, "The Friction and Lubrication of Solids," Oxford at the Clarendon Press, 1950, 337 pp.

Brockway, L. O., and J. Karle, "Electron Diffraction Study of Oleophobic Films on Copper, Iron and Aluminum," J. Colloid Science 2, 277-87, (1947).

Browning, G. V., L. E. Colteryahn, and D. G. Cummings, "Failure Mechanisms Associated with Thermocompression Bonds in Integrated Circuits," Symposium on Physics of Failure in Electronics 4, 428-46 (1966).

Cabrera, N. and N. F. Mott, "Theory of the Oxidation of Metals," Reports on Progress in Physics 12, 163-84 (1948-9).

Camp, E. K., "Electrodepositing Gold for Electrical Contacts," Proc. Third International Research Symposium on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 5 pp.

Camp, Eldridge K., "Tarnishing of Thin Rhenium Deposits on Nickel: Effect of Plating Process Anions and Ultrasonics," Plating 53(3), 318-19 (1966).

Campbell, W. E., "Studies in Boundary Lubrication - Variables Influencing the Coefficient of Static Friction Between Clean and Lubricated Metal Surfaces," Amer. Soc. Mech. Engrs., Trans. 61, 633-41 (1939).

Campbell, W. E. and Rose Kozak, "Studies in Boundary Lubrication --III The Wear of Carbon Brushes in Dry Atmospheres," Amer. Soc. Mech. Engrs., Trans. 70, 491-8 (1948).

Campbell, W. E., "Solid Lubricants," Lubrication Engineering, August, 1953, Vol. 9, pp. 195-200.

Campbell, W. E., "The Status of Fretting Corrosion, Part Two - Mechanism, Identification and Prevention of Fretting," Scientific Lubrication, December, 1953, Vol. 5, 18-22.

Campbell, W. E., "Current Status of Fretting Corrosion," Symposium on Fretting Corrosion, ASTM Spec. Tech. Publ. No. 144, 3-19, discussion 19-23 (1953).

Campbell, W. E., "Basic Mechanical and Electrical Principles Governing Sliding Contacts - Friction and Wear, Current-Voltage Relations," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1958, 2 pp.

Campbell, W. E., "Basic Mechanical and Electrical Principles Governing Sliding Contacts: Friction and Wear, Current-Voltage Relations," Engineering Seminar on Electrical Contacts, Penn. State Univ., 1960, pp. 75-6.

Chaston, J. C., "Materials for Electrical Contacts," Inst. Elect. Engrs. (London), J. 88 (Pt.II), 276-301 (Aug. 1941).

Chatfield, Chester H., "Silver and Silver Alloys, Properties and Design Applications," Electrical Manuf. 64(4), 167-71 (1959).

Chernowitz, George, "Reliability Prediction for Mechanical and Electromechanical Parts," American Power Jet Co., Ridgefield N. J., Contract No. AF30 602 2991, Proj. 5519, Task 551902, Monitor RADC, May 1964, 297 pp.

Chhabra, D. S. and G. T. Wenning, "The Effects of Surface Finish and Contact Geometry on Contact Resistance," Eng. Seminar on Electrical Contacts, Proc., Univ. Maine, Orono, Maine, 1965, pp. 315-39.

Church, H. F., "Factors Affecting the Life of Impregnated-Paper Capacitors," Proc. Instm. Elect. Engrs., Pt. III, 98, 113-22 (1951).

Church, H. F., and J. J. Walsh, "Investigation of Deterioration of Moulded Carbon Resistors: First Report.," The British Electrical and Allied Industries Research Association, Reference Z/T92, Sept. 21, 1953.

Church, H. F., "Oriented Polystyrene Film Capacitors. A Major Cause of Premature Breakdown," The British Electrical and Allied Industries Research Association, Reference L/T289, July 14, 1953.

Church, H. F. and J. J. Walsh, "Study of the Failure of Vitreous Enamelled Wire-Wound Resistors," The British Electrical and Allied Industries Research Association, Reference Z/T107, 1956.

Church, H. F., "Grade 2 Fixed Resistors," The British Electrical and Allied Industries Research Association, Reference Z/T113, 1958.

Church, H. F., "Detection of Organic Impurities in Insulation," The British Electrical and Allied Industries Research Association, Reference L/T375, 1958.

Church, H. F., "Electrical Insulation Faults," Electrical Review, Vol. 164 (7), Feb. 13, 1959, pp. 291-5.

Church, H. F., "The Long-Term Stability of Fixed Resistors," Proc. IEEE, vol. 107, pt. B, pp. 377-385, July 1960.

Church, H. F., "The Dielectric Properties of Anodic Aluminium Oxide Films," Proc. Inst. Elec. Engrs., Pt. B 109, Suppl. No. 22, 399-406, 453-6 (1962).

Church, H. F., "Research on Failure in Electronic Components," Brit. Commun. & Electronics, 357-9 (June 1965).

Church, H. F., and Z. Krasucki, "The Ageing of Power Capacitors: Effects Due to Ions and the Structure of Paper," The Electrical Research Association, Report No. 5142, 1965.

Clarke, M. and J. M. Leeds, "Porosity in Single and Multi-layer Electrodeposits, and its Relation to the Basis Metal State," Inst. of Metal Finishing, Trans. 43, 50-62, (1965).

Cocks, M., "Role of Atmospheric Oxidation in High Speed Sliding Phenomena," Journal of Applied Physics, Vol. 28, No. 8, Aug. 1957.

Colteryahn, L. E. and J. L. Kersey, "Failure Mechanisms and Kinetics of Intermetallic Formation," IEEE Nescon, Pt. 2, Tech. Papers (1965), 7 pp.

Compton, K. G. and R. G. Baker, "The Use of Electroplated Metals in Static Contacts," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1960, pp. 13-31.

Compton, O. R., "Is Power Equipment Failing Earlier," Electrical World 168, 36 (Nov. 27, 1967).

Conant, H. B., "Preventive Maintenance Keeps Relays Working," Radio Electronics 31, 71-2 (April 1960).

Cooper, R. I. B. and J. Pullen, "The Erosion of Tungsten and Rhenium Contacts by Arcing and by Spark Breakdown," Electrical Research Association, Ref. U/T144, 1961.

Cotton, J. B., "The Control of Surface Reactions on Copper by Means of Organic Reagents," Natl. Assoc. Corrosion Eng., Ext. Abstr., 1962, p. 117.

Cotton, J. B. and I. R. Scholes, "Benzotriazole and Related Compounds as Corrosion Inhibitors for Copper," Brit. Corros. J., 1967, Vol. 2, January, pp. 1-5.

Coughlin, James P., "Contributions to the Data on Theoretical Metallurgy XII. Heats and Free Energies of Formation of Inorganic Oxides," Bureau of Mines, Bulletin 542.

Cozzens, Bradley, and T. M. Blakeslee, "Performance of Dust-Contaminated Insulators in Fog," AIEE Trans. 67 (Pt.II), 1686-92 (1948).

Crawford, W. M., "Atmospheric Effects on Relay Reliability," Natl. Assoc. Relay Manufacturers, Natl. Conf. on Electromagnetic Relays, Tenth, Oklahoma State Univ., 1962, 5pp.

Culbertson, Allman T., "Air Force Turns Heat on Reliability," SAE J, pp. 79-80, Vol. 73, No. 3, (March 1965).

Cunningham, James A., "The Plagues in Semiconductor Contacts," The Electronic Engineer, Vol. 26, p. 39, April 1967.

Cunningham, J. A., and J. G. Harper, "Semiconductor Reliability: Focus on the Contacts," The Electronic Engineer, Vol. 26, pp. 74-9, Jan. 1967.

Curtis, A. M., "Contact Phenomena in Telephone Switching Circuits," Bell System Tech. J. 19, 40-62 (1940).

Daniel, S. G., "The Adsorption on Metal Surfaces of Long Chain Polar Compounds from Hydrocarbon Solutions," Trans. Faraday Soc. 47, 1345-59 (1951).

Daniels, R. O. and A. C. West, "The Influence of Moisture on the Friction and Surface Damage of Clean Metals," Lubrication Engineering, July-August, 1955, Vol. II (4); pp. 261-6.

Davies, T. A., "Electrical Contacts: Research and Reliability," Compon. Technol. (GB), Vol. 2, No. 7, 23-6 (Sept. 1967).

Dennison, Benjamin H., "Indent Depth and Configuration for Maximum Reliability of Nickel-Plated Copper Wire Crimped in Gold-Plated Connector Contacts," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 69-77.

Dennison, B. H., "Tropical Service Life of Electronic Parts and Materials," U.S. Army Electronics Command, Reference ECOM-02222-F, May 1968.

Dettner, Heinz W., "The Prevention of Silver Tarnishing," Plating 48, 285-7 (1961).

Dies, K., "Aus der Ingenieurforschung. Die Reiboxydation als chemisch-mechanischer Vorgang," VDI-Zeilschrift Bd. 87, Nr. 29 30 24 Juli 1943, pp. 475-6.

Dietrich, Isolde und Marlene Honrath-Barkhausen, "Zur Bildung widerstandserhöhender Beläge organischen Ursprungs auf elektrischen Kontakten," Zeitschrift fur angewandte Physik 11, 399-403 (1959).

Dietrich, Isolde, "Investigations with the Radioactive Tracer Method, Including Material-Transfer Measurements," Proc. International Research Symp. Electric Contact Phenomena, Univ. Maine, 1961, pp. 215-24.

Dilworth, (Miss) C. C., "The Influence of Surface Films on the Electrical Behaviour of Contacts," Proc. Phys. Soc., London 60, pp. 315-25 (1948).

Doctor, Norman J. and P. J. Franklin, "Corrosion of Copper Wire by Resins," Electronic Equipment, pp. 20-3 (July 1956).

Dummer, G. W. A. and N. Griffin, "Electronic Equipment Reliability," Sir Isaac Pitman & Sons, London, 1960, pp. 22-24.

Dummer, G. W. A., "Analyzing Failure Rates in Electronic Components," Electro-Technology 67, pp. 89-92 (February 1961).

Dummer, G. W. A., "The Anatomy of Reliability. Failure Rates, Long Term Changes and Failure Mechanisms of Electronic Components," Electronic Components, Vol. 5 (10), pp. 835-62, October 1964.

Dummer, G. W. A., "Fixed Resistors," 2nd ed., Sir Isaac Pitman, London, 1967, pp. 199-211.

Durbridge, C. F. D., "The Effect of Particle Size on the Lubricating Effect of Molybdenum Disulphide," Scientific Lubrication, June 1965, pp. 14-18, 26.

Egan, Thomas F., "Electrical Contacts," U.S. patent 2,812,406, November 5, 1957.

Elsey, Howard M., "Treatment of High-Altitude Brushes by Application of Metallic Halides," Trans. Amer. Inst. Electr. Eng. 64, 576-9 (1945).

Estorff, Walther and Werner Weber, "Abspritzen von Hochspannungsisolatoren im Betrieb," (Water Cleaning of Live H.V. Equipment), Elektrotechnische Zeitschrift, Sept. 5, 1940, pp. 817-22.

Evans, U. R., "The Practical Problems of Corrosion, Part V. Corrosion and Protection at the Contacts of Dissimilar Metals," Journal of the Society of Chemical Industry Transactions, Vol. 47, pp. 73-75, March 23, 1928.

Evans, Ulick R., "Metallic Corrosion Passivity and Protection," Edward Arnold & Co., 1948, 863 pp.

Fairweather, A., F. Lazenby and D. Marr, "Development of Resistance at a Disturbed Contact: With Special Reference to Silver, Copper and Nickel Silver," Instn Elect. Conf. Publ.(GB), 1965, No. 3, 3-1-3-4. (Components and Materials Used in Electronic Engineering Conference, London, May 1965).

Fairweather, A., and A. E. Parker, "Some Electrical Properties of 'Natural' Films Developed on Platinum Contacts," Inst. of Electrical Engineers, Conf. Publ. No. 12, 1965, 8 pp.

Falk, Howard, "New Relay Developments," Electro-Technol. 72(7), 143-6+ (July 1963).

Farber, Milton and Donald M. Ehrenberg, "High-Temperature Corrosion Rates of Several Metals with Hydrogen Sulfide and Sulfur Dioxide," J. Electrochem. Soc. 99(10), pp. 427-34 (Oct. 1952).

Ficchi, Rocco F., "In Equipment and Components . . . How Long-Term Storage Affects Reliability," Electronic Industries 25, pp. 42-8+(March 1966).

Fischmeister, H. and J. Drott, "Reaction Rate and Growth Forms of Reaction Product in the System Ag-H_2S," Acta Metallurgica, Vol. 7, December 1959, pp. 777-81.

Flom, D. G. and R. H. Savage, "Contact Resistance Measurements at Low Loads," Ann. N. Y. Acad. Sci. 58, 946 (1954); Gen. Elec. Rev. 58, No. 2, 59 (1955).

Forty, A. J. and P. Humble, "Surface Embrittlement and Stress Corrosion Cracking of Brass in a Tarnishing Solution," Natl. Assoc. Corrosion Eng., Ext. Abstr., 1962, p. 113.

Franken, Herbert, "Kontaktsicherheit in der industriellen Steuerung," (Contact Reliability in Industrial Control), Elektrotechnische Zeitschrift (ETZ) 14 (13), 349-53 (June 25, 1962).

Gaiennie, Daryl E., "Clean Insulators with Washer 'Gun'," Electrical World, Vol 153, March 28, 1960.

Gaillet, M. B., "Etude Experimentale in situ De La Tenue Dielectrique Superficielle, Sous La Tension De Service Normal, De Chaines D'Isolateurs Soumises A La Pollution Atmospherique," Bull. de la Societe Francaise des Electriciens 8, 574-86 (1958).

Garte, Samuel M., "Determination of the Porosity of Gold Electrodeposits by Quantitative Electrography," Plating 53(11), 1331-4 (1966).

Garte, Samuel M., "Effect of Substrate Roughness on the Porosity of Gold Electrodeposits," Plating 53(11), 1335-9 (1966).

Gerber, T., "Ambient Influence Upon Weak Current Contacts," Tech. Mitt. PTT (Switzerland), Vol. 44, No. 8, 233-49 (1966). In German and French.

Gerber, Theodor, "Umgebungsbedingte Einflüsse auf Schwachstromkontakte Influences du milieu ambiant sur les contacts pour courant faible," Technische Mitteilurgen PTT (Bern) 44(8), 233-49 (1966).

Germer, L. H. and F. E. Haworth, "Erosion of Electrical Contacts on Make," J. Appl. Physics, Vol. 20, November, 1949, pp. 1085-1109.

Germer, L. H., "Arcing at Electrical Contacts on Closure. Part I. Dependence upon Surface Conditions and Circuit Parameters," Journal of Applied Physics, Vol. 22, No. 7, July 1951, pp. 955-964.

Germer, L. H., "Arcing at Electrical Contacts on Closure. Part IV. Activation of Contacts by Organic Vapor," Journal of Applied Physics, Vol. 25, No. 3, March 1954, pp. 332-5.

Germer, L. H., "Physical Processes in Contact Erosion," Journal of Applied Physics, Vol. 29, No. 7, July 1958, pp. 1067-82.

Germer, L. H. and C. D. Hartman, "Oxygen on Nickel," Journal of Applied Physics, Vol. 31, No. 12, December 1960, pp. 2085-95.

Germer, Lester H., "Arcs in Opening Contacts," Proc. International Research Symposium on Electric Contact Phenomena, Univ. Maine, 1961, pp. 239-59.

Germer, L. H., "The Erosion of Relay Contacts," Wear, 3 (1960) 188-199.

Glowasky, Albert, "Investigation of Platings of Electrical Contacts," Naval Applied Science Lab, Project NASL-IED-20, Final Report, April 1968, 39 pp.

Godfrey, Douglas and Edmond E. Bisson, "Effectiveness of Molybdenum Disulfide as a Fretting-Corrosion Inhibitor," National Advisory Committee for Aeronautics, Technical Note 2180, Sept. 1950, 29 pp.

Goldie, W., "Anti-Tarnish Treatments for Silver," Electroplating and Metal Finishing, 16, pp. 336-42, (1963).

Goldie, W., "Anti-Tarnish Treatments for Silver," (concluded) Electroplating and Metal Finishing 17, 13-18 (1964).

Gordon, Kenneth H., "Contact Wire Wear," Trans. AIEE II 80, pp. 220-4, (1961).

Greenidge, R. M. C., "The Case of Reliability Versus Defective Components et al," Proc. 1953 Electronic Components Symp., Pasadena, Calif., April 29, 30, May 1, 1953, pp 19-1 - 19-8.

Grégoire, C., "Comportement Des Isolateurs De Lignus Et D'Appareillage En Pollution Naturelle Et Artificielle. Expériences Belges," (Behavior of Line Insulators and Line Equipment under Conditions of Natural and Artificial Pollution), Conference Internationale des Grands Res. Electriques (CIGRE), Paper 211 (1964).

Gregorovič, F., "Practical Tests on the Influence of Corrosion on Aluminium Steel Conductors," Elektroprivreda (Yugoslavia), Vol. 17, No. 2, 80-3 (Feb. 1964). In Slovenian.

Grilikhes, S. Ya. and D. S. Isakova, "Electroplating of Switching Contacts," Sotskov, B. S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT F-339, pp. 332-47.

Grunert, K. A., "Insure Reliable Electric Contacts," Power, 106, pp. 182-4 (August 1962).

Gumley, R. H., "Contact Phenomena in Sealed Containers," Bell Lab. Record 32, pp. 226-30 (1954).

Hakim, E. B., "The Application of Molybdenum Contacts for Improved Second Breakdown Performance," Proceedings of the IEEE, 54(6), 880 (1966).

Hämmerli, S., "Kontaktprobleme an schnellen Schaltsystemen," Schweizerischer elektrotechnischer verein bulletin 47 (26), 1195-1204+ (1956).

Hanks, C. L. and D. J. Hamman, "Final Report on A Study of the Reliability of Electronic Components in a Nuclear-Radiation Environment," Vol. I, Battelle Memorial Institute project on JPL Test No. 617, Phase II, Contract No. 950458, June 1, 1966.

Harada, S. and K. Mano, "The Effects of Surface Roughness on Constriction Resistance of Electrical Contact," Tohoku Univ. Res. Inst. of Electrical Communication, Repts. B 19 (1), 41-58 (1967).

Harada, S. and K. Mano, "Constriction Resistance of Electric Contact between Rough Flat Surfaces Considering Surface Roughness," Tohoku Univ. Res. Inst. of Electrical Communication, Repts. B 19 (2), 103-15 (1967).

Harada, S. and K. Mano, "The Effects of Surface Roughness on the Contact Resistance of Electric Contacts Covered with Tarnish Film," Tohoku Univ. Res. Inst. of Electrical Communication, Repts. B 19 (2), 117-24 (1967).

Harada, Seiki and Kunio Mano, "The Effects of Surface Roughness on Electrical Contact Resistance," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 47-52.

Harman, George G. and Theodore Higier, "Some Properites of Dirty Contacts on Semiconductors and Resistivity Measurements by a Two-Terminal Method," Journal of Applied Physics, Vol. 33, No. 7, July 1962, pp. 2198-2206.

Hart, W. P. and D. K. Sanders, "A System for the Recording, Reduction and Reporting of Component Reliability Test Data," Proceedings Thirteenth Annual Symposium on Reliability, Washington, 1967 (New York: Institute of Electrical and Electronics Engineers Inc., 717-27.)

Hathaway, C. B., "The Facts on Brush Wear and Silicone Insulation," Power Engineering 64, February 1960.

Hauffe, K., "Oxydation von Metallen und Metallegierungen," Springer-Verlag (Berlin/Göttingen/Heidelberg) 1956.

Haworth, F. E., "Electrode Reactions in the Glow Discharge," Journal of Applied Physics, Vol. 22, No. 5, pp. 606-9, May 1951.

Haworth, F. E., "Breakdown Fields of Activated Electrical Contacts," J. Applied Physics 28, 381 (1957).

Heil, V. E., P. C. Murphy and L. F. Neely, "The Evaluation of Rhenium as an Electrical Contact Material," Gonser, B. W., ed., Rhenium, Elsevier Publ. Co., N. Y., 1962, pp. 163-70.

Henderson, Wayne Lee Roy, "Why Does an Electrical Joint Heat?", Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1959, pp. 1-10.

Hentsch, A., "Neuere Untersuchungen und Entwicklungstendenzen auf dem Gebiet der elektrischen Kontaktwerkstoffe," (Recent Investigations and Developments in the Field of Electrical Contact Material), Elektrie Heft 5 (1962), Vol. 16 (5), pp. 149-52.

Hentsch, A., "Untersuchunger über den Widerstand sulfidierter Kontakte aus Silber und Silberlegierungen," (Investigations onthe Resistance of Sulphided Contacts Made of Silver and Silver Alloys), Elektrie (Germany) 16(7), 234-6 (July 1962).

Hentsch, A., "Untersuchungen Zum Feinwanderungsverhalten Von Silberkontakten," (Investigations about Bridge Transfer of Silver Contacts), Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 1 p.

Hermance, H. W. and T. F. Egan, "Examination of Contact and Other Surfaces by a Plastic Replica Technique," Proc. 1956 Electronic Components Symp., Washington, D. C., May 1, 2, 3, 1956, pp. 85-93.

Hermance, H. W. and T. F. Egan, "The Examination of Electric Contacts by the Plastic Replica Method," Trans. Amer. Inst. Elect. Engrs. 76, 756-62 (1957).

Higier, Theodore and George G. Harman, "The Contact Properties of Thin Films on Semiconductors," Proc. International Research Symp. on Elect. Contact Phenomena, Univ. Maine, Orono, Nov. 1961, pp. 31-8.

Hirst, W., M. Kerridge and J. K. Lancaster, "Variation with Load of the Coefficient of Friction and Metallic Transfer Under Conditions of Boundary Lubrication," Proc. Royal Soc.A 212, 512-20 (+plates)(1952).

Hirst, W. and J. K. Lancaster, "The Influence of Oxide and Lubricant Films on the Friction and Surface Damage of Metals," Proc. Royal Soc. A 223, 324-38 (1954).

Hirst, W. and J. K. Lancaster, "Surface Film Formation and Metallic Wear," Journal of Applied Physics, Vol. 27, No. 9, pp. 1057-65, Sept. 1956.

Hodges, William H., "Study and Analysis on the Utilization of Solderless Wrapped Electrical Connections," Army Missile Command Redstone Arsenal ala Army Inertial Guidance and Control Lab, Project DA-1B278181-D678, March 1966, 17 pp.

Hofmann, Heinz, "Metallischer Verschleib durch Reiboxydation," (Metallic Wear by Fretting Corrosion), Wissenschaftliche Zeitschrift der Hochschule für Maschinenbau Karl-Marx-Stadt . 2 (1960) Heft 3, pp. 259-64.

Höft, H., "Die Übertemperatur an elektrischen Kontakten mit Fremdschicht," (The Heating in Electrical Contacts which Are Contaminated by Surface Films), Wiss. Z. Hochsch. Elektrotech. (Ilmenau) 12 (2), 155-8 (1966).

Höft, H., "Fragen der Zuverlässigkeit von elektrischen Kontakten," (On Reliability of Electric Contacts), Nachrichtentechnik, 17 (5), 200-4 (May 1967).

Holm, Ragnar, "Elektrische Kontakte in MeBgeräten," ATM Archiv für Technisches Messen, No. 175, pp. T95-6 (August 1950).

Holm, Else und Ragnar Holm, "Die Stoffwanderung in Abhebekontakten aus Silber und Platin," (The Transfer of Matter at Break of Contact, in the Case of Silver and of Platinum), Zeitschrift fur angewandte Physik 6, 352-61 (Aug. 1954).

Holm, Ragnar, "Theorie der ungleichen Stromverteilung im Kontakt zwischen Kohlebürsten und Schleifringen aus Kupfer oder Stahl in Luft," (Theory of the Unequal Current Distribution in Contacts between Carbon Brushes and Copper or Steel Rings in Air), Elektrotechniche Zeitschrift (ETZ) A 81 (16), 570-1 (Aug. 1, 1960).

Holm, Ragnar, "Electric Contacts, Theory and Application," Fourth Ed., Springer-Verlag New York Inc. 1967, 482 pp.

Holm, Else, "Calculation of the Interlamellar Bond Strength across Orientated Graphite Layers during Smooth Sliding," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 95-9.

Holmes, P. J. and I. Jennings, "Studies of Failure Mechanisms and Diagnosis of Failures in Semiconductor Devices," Royal Aircraft Establishment Farnborough (England), Report No. TR-66166, May 1966, 61 pp.

Hooper, Robert C. and Louay E. Sharif, "Metal-Semiconductor Contact Resistance," Engineering Seminar on Electrical Contacts, Proc., Univ. Maine, Orono, Maine, 1965, pp. 47-61.

Hopwood, W., "The Characteristics of Toughened Glass Overhead Line Insulators and Some Particular Aspects of Insulator Performance in Service," Trans S. African Inst. Elect. Engrs, Vol. 58, Pt. 9, 189-210 (Sept. 1967).

Hudson, A. A., "Degradation of SF_6 in Electrical Equipment: Toxic and Corrosive Effects. A Resume of Published Information," ERA Rep. (GB), Rep. 5185, 38 pp. (1967).

Hughes, D. M. "An Ultrahigh Vacuum System for the Preparation and Study of Surface Properties of Cadmium Sulphide Thin Films," Vacuum/vol. 17/ No. 10. Pergamon Press Ltd/Printed in Great Britain, 1967, pp. 555-8.

Hughes, T. P. and G. Whittingham, "The Influence of Surface Films on the Dry and Lubricated Sliding of Metals," Trans. Faraday Soc 38, 9-27 (1942).

Hunt, M. P., "Preventive Maintenance of Major Electrical Equipment," Safety Maintenance 131, 48-50 (June 1966).

Hyde, N. E., "Special Quality Miniature Relays," Brit. Commun. and Electronics 7 (5), 338-45 (1960).

Iosipyan, E. S., "A Study of the Resistance to Corrosion of Contact Pairs of (Dissimilar) Metals under Tropical Conditions," Elektrotekhnika (USSR), Vol. 38, No. 10, 47-50 (1967). In Russian. English translation in: Soviet Elect. Engng (USA).

Ittner, W. B., III, and P. J. Magill, "A Survey of Contact Resistance Theory for Nominally Clean Surfaces," IBM Journal, Vol. 1, pp. 44-8, (January 1957).

Jakubowski, George C., "Recent Developments in Switches for Miniature and Transistorized Equipments," Proc. 1955 Electronic Components Conference, 6th Annual, Los Angeles, Calif., May 26, 27, 1955, pp. 32-3.

Jandial, A. P. and R. L. Spade, "A Study of the Effects of Long Term Exposure to Rated Operating Temperature upon Electrical Properties of Lead Wire Insulation," Proceedings Seventh Electrical Insulation Conference, Chicago, 1967 (New York: Institute of Electrical and Electronics Engineers, Inc., 1967) pp. 226-32.

Jaski, Tom, "Relays, Installing, Testing and Maintaining Them, with Special Attention to Modernization and Modification Jobs," Radio Electronics 33, 46-8 (Jan. 1962).

John, W. J., and F. M. Sayers, "Transmission-Line Insulators under Deposit Conditions," Inst. of Electrical Engineers J. 77, 629-62 (1935).

Johnson, J. A. and N. M. Bashara, "Thickness Effects of Electron Scattering at Au-Film Surfaces," Journal of Applied Physics, Vol. 38, No. 6, pp. 2442-61.

Johnson, J. L., and L. E. Moberly, "Brush Life and Commutation in Atmospheres of Air, SF_6 and CO_2," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 111-16.

Johnson, John, Roy T. Henderson, William S. Price, Dale E. Hedman, and Frederick J. Turner, "Field and Laboratory Tests of Contaminated Insulators for the Design of the State Electricity Commission of Victoria's 500-kV System," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-87, No. 5, May 1968, pp. 1216-39.

Jones, F. L., "The Physics of Electrical Contacts," Clarendon Press, Oxford, 1957, pp. 193-211.

Jones, L. K., "Materials and Process Variables and Their Effect on Contact Resistance," Engineering Seminar on Electrical Contacts, Penn. State Univ., 1960, pp. 52-63.

Jones, S. P., "Electrical Contact Production - Methods and Problems," Eng. Seminar on Electrical Contacts, Proc., Penn. State Univ., 1961, pp. 30-44.

Jordan, Bruce, "In-Plant Commutator Maintenance Saves $600 a Year," Plant Engineering, 20, 130-1 (March 1966).

Jost, E. and Edgar Freudiger, "Kinetics and Thermodynamics of the Internal Oxidation of Silver Cadmium," Proc. International Research Symp. on Electric Contact Phenomena, Univ. Maine, 1961, pp. 179-97.

Kamoshita, Gen-ichi, M. Hirano and N. Hara Hitachi, "Inhibiting Effect of PBS Addition to Brown Powder Formation on PD Alloys," Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 8 pp.

Kape, J. M. and J. A. Whittaker, "Five-Year Exposure Tests on Anodized Aluminium in a Severe Industrial Atmosphere," Trans Inst. Metal Finishing (GB), Vol. 43, Pt 3, 106-11 (Summer 1965).

Kataev, G. A., V. A. Presnov, E. N. Batueva, Yu. G. Kataev, and L. A. Lyuze, "Effect of the Adsorption of Certain Amines on a Semiconductor Surface on the Principal Parameters of Germanium Transistor Triodes," Frumkin, A. N., ed., Surface Properties on Semiconductors, transl. from Russian, 1964, pp. 151-5.

Keefer, H. J. and R. H. Gumley, "Relay Contact Behavior under Non-Eroding Circuit Conditions," Bell Syst. Tech. J. 37, 777-814 (May 1958).

Keil, Albert, "Die Bedeutung des „Kleinklimas" in gekapselten Schaltgeräten," (The Significance of the 'Little Climate' in Enclosed Switchgear), Elektrotechniche Zeitschrift (ETZ) B 12, 264-5 (May 30, 1960).

Keil, A., "Über spezielle chemische Reaktionen an Edelmetall-Oberflächen," (On Specific Chemical Reactions on Noble-Metal Surfaces), Metall 15 (7), 655-7 (1961).

Keil, A., "Können galvanische Edelmetallüberzüge die Spannungskorrosion bei Messing verhindern?", (Can Galvanic Noble-Metal Coatings Inhibit Stress Corrosion in Brass?), Galvanotechnik (Saulgau/Württ) 53 (1962) Nr. 2, pp. 95-6.

Keil, A., "Der elektrische Kontakt als Gegenstand der Forschung und eines internationalen Erfahrungsaustausches," (The Electric Contact as the Subject of Research and of an International Exchange of Experience), Bull. Assoc. Suisse Elect. (Switzerland) 55 (2), 51-8 (Jan. 25, 1964).

King, G. E. S., "Thermal Life of Silicone Rubber Can Be Predicted by Solvent Immersion," Electrical & Electronics Abstracts Vol. 71, No. 841 (January 1968).

Kisliuk, P. P., "Arcing at Telephone Relay Contacts," Bell Laboratories Record, 34, 218-22 (1956).

Kisliuk, P., "Using Contact Resistance to Measure Adsorption of Gases on Metals," Bell Syst. Tech. J. 37 (4). 925-49 (1958).

Kleis, John D. and Gilbert Halverson, "Contact Assembly," U.S. patent 2,547,947, April 10, 1951.

Kleis, John D., "Electrical Contact Disk of Silver-Germanium Alloy," U.S. patent 2,548,164, April 10, 1951.

Kleis, John D., "Electrical Contact Materials," Electrical Manuf. (Electro-Technology) 55, 102-7 (April 1955).

Kohman, G. T., "The Migration of Silver Through and on the Surfaces of Insulating Materials," Proc. Electronic Components Conference, 6th Annual, May 26, 27, 1955, Los Angeles, California, pp. 13-18.

Kohman, G. T., H. W. Hermance and G. H. Downes, "Silver Migration in Electrical Insulation," Bell Syst. tech. J., Vol. 34, No. 6, 1115-47 (Nov. 1955).

Kosco, John C., "Contact Materials: New Powder Composites," Electro-Technology, Vol. 77 (5), p. 43, May 1966.

Kowal, Leo, "Why Motors Fail," Plant Engineer 15, 122-3 (April 1961).

Krasucki, Z., H. F. Church, and C. G. Garton, "A New Explanation of Gas Evolution in Electrically Stressed Oil-Impregnated Paper Insulation," J. Electrochem. Soc. 107 (7), 598-602 (July 1960).

Krasucki, Z., H. F. Church and C. G. Garton, "Factors Controlling the Life of Power Capacitors," CIGRE Paper 138 (1962).

Krasucki, Z., "Processes Leading to Discharges in Oil-Impregnated Paper," Proc. Inst. Elec. Engrs., Pt. B 109, Suppl. No. 22, 435-9 (1962).

Krasucki, Z. and H. F. Church, "The Detection of Ionic Impurities in Insulation," Proc. Inst. Elect. Engrs. 109A, Suppl. No. 3, 14-21 (1962), 49-51.

Krause, H. H., "Sulfur Oxide Reactions: Radioactive Sulfur and Microprobe Studies of Corrosion and Deposits," Series A, J. Eng. Power 90 (1), 38-44 (1968).

Krýže, J and V. Šilhán, "Uniselectors from the Point of View of Reliability," Automatizace (Czechoslovakia) Vol. 9, No. 2, 44 (1966).

Kučera, J., "Statistical Appraisal of the Insulation Performance on Transmission Lines with Switching Surges," Acta Tech. CSAV (Czechoslovakia), Vol. 12, No. 4, 502-12 (1967).

Lagus, M., "Factor in Designing Switches, Relay Contacts and Plugs and Sockets," Sahko (Finland), 1967, No. 7-8, 190-3 (July-Aug.).

Larpenter, Carl R., "A Reminder-Maintain Those Protective Relays, Power Engineering, Vol. 67, p. 66, August 1963.

Läser, L. und D. Klein, "Neues Anlauf-Schutzmittel für Silber," Internationale Elektronische Rundschau 22 (5), 118 (1968).

Laskie, J. R., "The Use of Molded Activated Carbon Getters in Sealed Electrical Instruments," ASTM Bull., No. 241, 41 (Oct. 1959).

Last, F. H., "Live Washing of H.V. Insulators in Polluted Areas and Surface Coatings for H.V. Insulators in Polluted Areas," Proc. IEE, Vol. 113, No. 12, Dec. 1966, pp. 2005-9.

Lawrence, Roland B., "Reliability Evaluation Criteria for Cylindrical Electrical Pin and Socket Contacts," IEEE Transactions on Aerospace-Support Conference Procedures AS-1 (2), 942-9 (1963).

Lawson, G. R., "Generation of Fast-Growing Whiskers in the Neighborhood of Arcing Metallic Contacts," Proc. International Research Symposium on Electric Contact Phenomena, Univ. Maine, 1961, pp. 287-97.

Lee, Henry, "Compatibility of Magnet Wire Insulations and Epoxy Encapsulating Resins," ASTM Bull. No. 247, 69-73 (July 1960).

Leighton, A. G., "Electromechanical Switching Devices--Reliability, Life and the Relevance of Circuit Design," Microelectronics and Reliability, Pergamon Press 1966, Vol. 5, pp. 161-173. Printed in Great Britain.

Leur, R., "Defects at Electrical Contacts Owing to Corrosion," PTT-Bedrijf (Netherlands) Vol. 15, No. 3,236-42 (July 1967). In Dutch.

Levine, J. H., "Finding Failure-Prone Components," Electro-Technology 80, 51-3 (Oct. 1967).

Licari, J. J. and G. V. Browning, "Plastics for Packaging: Handle with Care," Electronics 40, 101-8 (April 17, 1967).

Llewellyn Jones, F., "Electrical Properties of Tungsten Oxide Films," Nature, 157, 371-2, March 23, 1946.

Llewellyn Jones, F., "Electrode Ionization Processes and Spark Initiation," Proc. Phys. Soc. 62, 366-76 (1949).

Llewellyn Jones, F., "Arcing Phenomena at Electrical Contacts as Used in Communication Engineering," Inst. Elect. Engrs., Proc. 96 (Pt.1), 305-12 (1949).

Llewellyn Jones, F., and R. H. Jones, "The Formation and Rupture of Molten Metal Bridges in Electrical Contacts," Zeitschrift für Physik, Bd. 147, S. 43-58 (1957).

Llewellyn Jones, F., "The Physics of Electrical Contact Phenomena," Proc. International Research Symp. on Elect. Contact Phenomena, Univ. Maine, Orono, Nov. 1961, pp. 3-18.

Machlin, E. S. and W. R. Yankee, "Friction of Clean Metals and Oxides with Special Reference to Titanium," Journal of Applied Physics, Vol. 25, No. 5, May 1954, pp. 576-81.

Macklen, E. D., "Investigation of the Electrical Contact Properties of Granular Carbon Aggregates," Brit. J. of Applied Physics, Vol. 12, 443-6 (Sept. 1961).

Macklen, E. D. and B. Hodgson, "Electrical Contact Properites of Granular Carbon Aggregates: Part 2 -- Correlation Between Contact Resistance and Oxygen Content," Brit. J. Appl. Phys., 1962, Vol.13, pp. 171-2.

Macklen, E. D., "Electrical Contact Properties of Granular Carbon Aggregates. Part 3 -- Effects of Prolonged Air Oxidation," Brit. J. Appl. Phys., 1963, Vol. 14, pp. 28-30.

Magie, P. M., "Niobium Diselenide Powder," (An electrically conductive solid lubricant for extreme temperature/high vacuum use), BEMOL, Inc., Technical Sheet #207, June 1, 1965.

Mano, Kunio, "Static Contacts," Proc. International Research Symp. on Elect. Contact Phenomena, Univ. Maine, Orono, Nov. 1961, pp. 161-75.

Marinan, J., "Ups Motor Output 24%, Cuts Maintenance 75%," Food Engineering, Vol. 35, September 1963.

Marks, Bob, "How Can We Stretch Motor Life?", Power, Vol. 108, pp. 122-4, Jan. 1964.

Mason, W. P., and T. F. Osmer, "Solderless Wrapped Connections - Part II -- Necessary Conditions for Obtaining a Permanent Connection," Bell System Tech. Journal 32, 557-90 (May 1953).

Mauch, H., "Damage Caused at Two P.B.X.'s by Evaporations from Floor Coverings," Tech. Mitt. PTT (Switzerland), Vol. 45, No. 9, 522-3 (1967). In French and German.

Mahler, Paul, "Contamination of Sealed Switching Devices for Special Weapons," National Assoc. Relay Manufacturers, Natl. Conf. on Electromagnetic Relays, Tenth, Oklahoma State Univ., 1962, 21 pp.

Mauch, Hans, "Durch Ausdünstungen eines Bodenbelages hervorgerufene Schäden an zwei Hauszentralen," Technische Mitteilungen PTT (Bern) 45, 522-3 (1967).

Mauch, H., "Determination of the Vapour Pressure of Plasticizers and Insulation of Plasticizer Vapours in Air," EE. Abrst. 1960, No. 7558.

Mayeur, J. P., "Etude de la longévité probable des condensateurs au papier," Schweizerische technische zeitschrift (STZ) 57 (20), 419-23 (May 1960).

Melse, J. L. and P. Baeyens, "Protecting Silver and Copper Against Tarnishing by Means of a Chromate Passivating Process," 46th Annual Tech. Proc. Amer. Electroplaters' Society, Detroit, Mich., 1959, pp. 293-7.

Merl, W. "Die Stoffwanderung an Kontakten aus Edelmetall-Legierungen und ihre Abhängigkeit von der thermischen Vorbehandlung," Metall 15 . JG, July 1961, Heft (7) pp. 672-4.

Merl, W. A., "Concerning Material Loss in Silver Electrodes Caused by Transient Arcing at High Currents in Different Atmospheres," Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 7 pp.

Merl, W. A., "Material Losses on Silver Electrodes Subjected to Heavy-Current Short-Duration Arcs in Various Atmospheres," Elettrotecnica (Italy), Vol. 53, No. 10, 738-42 (Oct. 1966).

Millet, J., "Behavior of Carbon Brushes in Dry and Wet Atmosphere," Proc. 4th Conf. on Carbon, Univ. Buffalo, Buffalo, N.Y., 1960, pp. 719-25.

Millian, Kurt und Werner Rieder, "Kontakwiderstand und Kontaktoberfläche," Zeitschrift für angewandte Physik, 8, 28-34 (1956).

Mills, G. W., "Comparing Permanent Electrical Connections," Bell Lab Record 41 (9), 366-9 (1963).

Mills, G. W., "A Comparison of Permanent Electrical Connections," Bell System Tech. J. 43 (3), 1067-1102 (1964).

Mills, R., "Electrodeposited Contact Metals - An Evaluation of Selected Finishes for Printed Circuit Edge-Connector Contacts," Electroplating and Metal Finishing 20, 70-74 (March 1967).

Moberly, L. E., and J. L. Johnson, "The Effect of Variable High-Altitude Humidity on the Wear of Nondusting Brushes," AIEE, Applications and Industry, No. 44, 263-7 (Sept. 1959).

Moberly, L. E., "Performance of Silver Contacts in Atmospheres Containing Silicone Vapors," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1959, pp. 117-27.

Moberly, L. E., "Performance of Silver Contacts in Atmospheres Containing Silicone Vapors," Insulation 6 (4), 19-24 (1960).

Monashkin, M. R., "Preparation of Aluminum Conductors for Stable Electrical Connections," Trans. AIEE, Power Apparatus Systems, No. 44, 729-32 (1959).

Mooradian, Victor G., "Selecting Materials for Electrical Contacts," Materials Engineering 44, 121-40 (Sept. 1956).

Moore, A. J. W., and W. J. McG. Tegart, "Rupture of Oxide Films During Repeated Sliding," Australian J. Scientific Res. 4, 181-4 (1951).

Mott, N. F., "The Theory of the Formation of Protective Oxide Films on Metals. -- III." Trans. of the Faraday Soc. 43 (7), 429-34 (1947).

MacDonald, R. W., and H. W. Hermance, "A New Method for Cleaning Wire-Spring Relays," Bell Laboratories Record, 36, 30-3 (1958).

McGaughan, J. P., "Salvaged Connectors Save $50,000 Annually," Electrical World, June 26, 1961, Vol. 155.

Nestler, C. and D. Lange, "Investigations (and Their Results) of Corrosion Damage to Cd-Plated Parts," Technik (Germany), Vol. 22, No. 8,496 (Aug. 1967). In German.

Nicholls, W. J., and F. G. McDonald, "Aluminium Conductors for Overhead Lines," Proc. Instn. Elect. Engrs. (GB) 114 (9), 1274-82 (1967).

Nieske, F. W., "Reversion of Polyurethane and Polyacrylate Rubber Encapsulating Compounds in Humid Environments and Development of a Standard Reversion Test," Naval Avionics Facility, TR 1201, April 15, 1968.

Noonan, Harry J., "Electrographic Determination of Porosity in Gold Electrodeposits," Plating 53 (4), 461-70 (1966).

Nunn, Charles P., "Achieving Optimum Reliability in Miniature Relays," Electro-Technology, Vol. 8, 91-2, August 1967.

Oliver, Frank J., "Contacts Stressed at Relay Conference," Electro-Technology, August 1965, Vol. 76, pp. 69-72.

Omori, T., "Experimental Evaluation of Change in Resistance and Temperature Rise of Model Contacts with Time," Electrical Engineering in Japan (USA) 83 (11), 58-67 (Nov. 1963).

Orth, Henry S., "Testing and Maintenance of Protective Relays and Circuit Breakers," Electrical Construction and Maintenance, 63, 84-6, (Dec. 1964).

Pardee, R. P., "Moisture Dependence of Silver-Graphite Brushes in Air, Nitrogen, Helium, and Carbon Dioxide," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-86, No. 5, May 1967, pp. 616-25.

Parker, Edward A., "Electrodeposition of Rhodium," Plating 42, 882-92 (July 1955).

Parker, Edward A., "Recent Developments in Gold Alloy Plating," Plating 45, 631-5 (1958).

Pearse, James N., "Bibliography of Reed-Type Contacts and Devices," IEEE Transactions on Parts, Materials and Packaging, Vol. PMP-3, No. 3, September 1967, pp. 105-12.

Pfisterer, Hermann und Ekkehard Fuchs, "Identifizierung von Kontaktverunreinigungen mit elektronenoptischen Verfahren," Siemens Zeitschrift, Vol. 34, pp. 484-8, August 1960.

Pittman, Paul, "Integrated-Circuit Reliability," Electro-Technology, Vol. 75 (1), pp. 37-40, Jan. 1965.

Pocock, Walter E., "A Survey of Chromate Treatments," Metal Finishing, Vol. 52, pp. 48-51, Dec. 1954.

Pohl, J., "Materialwanderung und Kontaktwiderstand an Agse- und AgCd-Kontakten bei verschiedenen Induktivitäten bzw. bei verschiedener Belastung," Wiss. Z. Hochsch. Elektrotech. (Ilmenau) 5 (2-3)(1959).

Pohl, Z., "Importance and Selection of the Design of the Insulator Sheds for Polluted Conditions on the Basis of Model Tests," Przeglad Elektrotech. (Poland), Vol. 43, No. 8, 355-61 (August 1967). In Polish.

Pommerening, Uwe A., "A Practical Guide to Contact Applications," Natl. Assoc. of Relay Manuf. Symp., Ninth, Okla. Inst. Technol., Stillwater, Okla., 1961, pp. 21-7.

Pucher, W., "Moisture in the Air in Compressed-Air Switch-Gear," Elektrotech. Z. (ETZ) A (Germany), Vol. 86, No. 6, 172-5 (19 March 1965). In German.

Pullen, J., "Printed-Circuit Connectors - Contact Problems," Electronic Components, Vol. 5 (7), pp. 582-5, July 1964.

Raju, M. S. and G. J. V. J. Raju, "Studies on Breakdown Voltage of Anodized Aluminium Surfaces," J. Inst. Engrs. (India), Chem. Engng. Div. Vol. 48, No. 2, 19-27 (Oct. 1966).

Ramachandran, S. and R. Aravamudhan, "Reduction of Tarnishing of Electroplated Silver," Metal Finishing, Vol. 64, pp. 78-80, October 1966.

Reichman, S. H., and C. D'Antonio, "Electrical Resistivity of Vapor-Deposited Silver Films," Transactions of the Metallurgical Society of AIME, Vol. 242, Jan. 1968, pp. 160-1.

Reid, F. H., "Palladium Plating -- Processes and Applications in the United Kingdom," Plating 52, (6), 531-9 (1965).

Renaut, P. W., and T. Stathos, "Evaluating Sealed Contacts," Bell. Lab. Record (USA), Vol. 44, No. 5, 155-8 (May 1966).

Rice, L. A., "Design of an Ignition Contact Oxidation Test," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., 1956, 14 pp.

Rönnquist, A., and H. Fischmeister, "The Oxidation of Copper," Journal of the Institute of Metals, 89, 65-76 (Oct. 1960).

Rosenberg, R. C., "The Effect of Mechanically Dispersed Solid Powders on Wear Prevention by White Oil at High Loads and Low Speeds," Lubrication Engineering, Vol. 24, pp. 92-8, Feb. 1968.

Rowland, P. R., "Solderless Connections, A Consideration of Basic Concepts," Electrical Times, 31 March, 1960, pp. 491-5.

Roy, Eugene H., "Maintaining Complex Control Systems," Automation 12 (6), 158+ (1965).

Ruka, R. J., "Fundamental Aspects of the Oxidation of Contact Materials," Proc. Engineering Seminar on Electrical Contacts, Penn. State Univ., 1956, 33 pp.

Rybin, G. Ya., "The Reliability of Electromagnetic Relay Contacts According to Operational Data," Sotskov, B. S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT F-339, pp. 385-7.

Saito, Seizo, "Consideration of the Various Phenomena of Metal Wear and Influence of Atmospheres on the Wear of Steel," Jap. Soc. of Mech. Eng., Trans. 5, S-88-90 (1939).

Sakatos, M. J., "Increasing the Reliability of Sealed Relays in Electronic Equipment," Proc. 1955 Electronic Components Conference, 6th Annual, Los Angeles, California, May 26, 27 1955, pp. 37-9.

Sanders, William J., "Laboratory and Field Evaluation of Connectors and Other Accessories for Aluminum Conductors in Severe Marine Environments," Trans. AIEE, Power Apparatus Syst. No. 45, 1342-53 (1959).

Savage, R. H., "Carbon-Brush Contact Films," General Electric Review, 48, 13-20 (Oct. 1945).

Savage, Robert H., "Graphite Lubrication," Journal of Applied Physics, Vol. 19, No. 1, pp. 1-10, Jan. 1948.

Savage, Robert H., "Physically and Chemically Adsorbed Films in the Lubrication of Graphite Sliding Contacts," Annal. New York Acad. Sci. 53, 862-9 (1951).

Scarlett, N. A., "Greases to Prevent Fretting Corrosion," Engineering, Vol. 189, pp. 424-5, March 25, 1960,

Schmidlin, Fred W., "Enhanced Tunneling through Dielectric Films due to Ionic Defects," Journal of Applied Physics, Vol. 37, No. 7, June 1966, pp. 2823-32.

Schröter, F., "The Effect of Temperature on Sliding Contacts," Elektrotech. Z. (ETZ) A (Germany), Vol. 85, No. 18, 568-75 (4 Sept. 1964).

Schulze, Gerhard, "Static Input Devices," Siemens Rev. (Germany) 34 (9), 325-6 (1967).

Schumb, Walter C., John G. Trump and Grace L. Priest, "Effect of High Voltage Electrical Discharges on Sulfur Hexafluoride," Ind. and Eng. Chem. 41 (7), 1348-51 (1949).

Selikson, B., and T. A. Longo, "A Study of Purple Plague and its Role in Integrated Circuits," Proceedings of the IEEE, 52, 1638-41, Dec. 1964.

Savage, Robert H. and D. L. Schaefer, "Vapor Lubrication of Graphite Sliding Contacts," Journal of Applied Physics, Vol. 27, No. 2, Feb. 1956, pp. 136-8.

Savchenko, V. S., "Determining Norms from the Basic Electric Parameters of Connector Contacts, Sotskov, B. S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT F-339, pp. 407-25.

Sellers, W. D., "Relay Contact Contamination," Natl. Assoc. Relay Manuf., Natl. Conf. Electromag. Relays, Conf. Proc. 14th Annual, Oklahoma State Univ. 1966, pp. 96-7.

Shilliday, T. S., "Physics of Failure in Electronics, Volume V.," Battelle Memorial Inst., Report No. AD 655 397, 574 pp. 1966.

Shobert, Erle. I, II, "Recent Advances in Sliding Contacts Including Space Applications," IEEE International Conv. Record 14 (9), 18-21 (1966).

Shtremberg, T. K. and N. A. Belozerova, "The Useful Life of Platini-Iridium Relay Contacts as a Function of Load Current," Sotskov, B. S., et al, Electric Contacts, Moscow - Leningrad, 1964, NASA TT F-339, pp. 388-406.

Sims, R. F., "The Wear of Carbon Brushes at High Altitudes," Proc. Inst. Elect. Engrs. II, 101, 217-26 (1954).

Smith, Maurice N., "Investigation of Commercially Available Two-Way Electrical Connectors and Techniques Used with Dissimilar Conductors (Aluminum-Copper), Naval Civil Eng. Lab project, Report No. NCEL-TN-911, Project Y-F015-12-06-910, July 1967, 19 pp.

Solos, L. P., "Fundamental Study of a Gold Plating and Dry Film Lubricant System for Long Life Sliding Electric Contacts," Proc. Natl. Aerospace Electronics Conf., Dayton, Ohio, May 11-13, 1964, pp. 117-23.

Snowball, R. F., J. B. P. Williamson, R. C. Hack, " The Ingress of Reactants Between Contacting Surfaces," Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 6 pp.

Sotskov, B. S., I. Ye. Dekabrun, B. N. Zolotykh, R. S. Kuznetsov, and Z. S. Kirillova, "Electric Contacts," (Translation of "Elektricheskiye kontakty." Izdatel'stvo Energiya, Moscow - Leningrad, 1964), NASA TT F-339.

Soucy, C. I., "A Broad Survey of the Military Electronic Equipment Reliability Problem and its Controlling Factors," Proc. 1956 Electronic Components Symp., Washington, D. C., May 1, 2, 3, 1956, p. 12.

Soulages, M. G., "Evolution Dans La Technique Des Condensateurs," Society Franciase des Electriciens, Bull. 9, 449-60 (Nov. 1959).

Spengler, H. F., G. Rau Double Fabrik, "Disperson Hardened Silver Alloys -- New Materials for Electrical Contacts," Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 1 p.

Spergel, Jack, "Misleading Requirements on Specifications for Sliding Contact Forces," Reliable Electrical Connections, Engineering Publishers, N. Y., 1959, pp. 59-73.

Spergel, Jack and Elmer Godwin, "A Thin Film Lubricant for Connector Contacts," IEEE Trans. Parts, Materials, Pkg. PMP-1 (1), S-1-S-9 (1965).

Spry, W. J. and P. M. Scherer, "Film Studies of Copper Oxide at a Sliding Electrical Contact," Engineering Seminar on Electrical Contacts, Proc., Penn. State Univ., 1961, pp. 76-83.

Spry, W. J. and P. M. Scherer, "Copper Oxide Film Formation at a Sliding Carbon-Copper Interface," Wear, 4 (1961) 137-149.

Steinberg, Gunther and Saul W. Chaikin, "Lubrication of Electrical Contacts with Solid Thin Films of Organic Compounds," Proc. Third International Research Symp. on Electric Contact Phenomena, Univ. Maine, Orono, June 1966, 13 pp.

Steiner, R. G., H. G. Meyer, "Silicone Eases Icy Switch Action," Electrical World, Vol. 154, pp. 74-, Sept. 26, 1960.

Stephen, K., "Lubrication of Rotary Switch Contacts," Engineering Seminar on Electrical Contacts, Proc., Penn. State Univ., 1961, pp. 84-94.

Stepke, E. T., "Electrical Conduction Processes through Very Thin Tarnish Films Grown on Copper," Electrical Contacts, Proc. of the Engineering Seminar on Electric Contact Phenomena, 1967, pp. 127-35.

Sulyok, J., "Problems of the Application of Moulded Plastics to Electrical Apparatus in Damp Tropical Circumstances," Plaste u. Kautschuk (Germany), Vol. 14, No. 5, 320-2 (May 1967). In German.

Summers, N. D., "'Dirt' in Relays -- Its Cause, Effect and Control," Electronic Components (GB), 7 (11), 1046-9 (Nov. 1966).

Swanson, Frank D., "Differential Thermal Analysis (DTA) Indicates Volatile Products and Moisture Present in Nylon," Insulation, Vol. 11 (11), 33-6, Oct. 1965.

Swanson, Robert E., "A Stable Point Contact Transistor," Proc. 1955 Electronic Components Conference, 6th Annual, Los Angeles, Calif., May 26, 27, 1955, pp. 51-3.

Swinehart, Merle R., "Switches -- The Effect of Oxygen on the Arc Erosion Properties of Silver Contacts," Proc. International Research, Symposium on Electric Contact Phenomena, Univ. Maine, 1961, pp.301-16.

Taylor, J. J., "Insulators to Withstand Air-Borne Deposits," AIEE Trans. 67 (Pt. II), 1436-41 (1948).

Taylor, T. C., "Characteristics of Soft Metals for Electrical Connexions," Microelectronics and Reliability (GB), Vol. 6, No. 2, 125-34 (May 1967).

Thomas, U. B., "Contact Resistance Characteristics of Various Metals before and after Tarnishing for 12 Weeks in Barclay Central Office Case 36497," Bell Telephone Report MM-37-323-40, April 1937, 20. pp.

Thomas, U. B., "The Use of Electroplated Metal in Static Contacts," Proc. International Research Symp. on Elect. Contact Phenomena, Univ. Maine, Orono, Nov. 1961, pp. 109-17.

Thompson, J. E. and M. J. B. Turner, "The Part Played by a Metal Oxide in Determining the Characteristics of a Graphite-Metal Interface," Wear, 6 (1963) 30-43.

Thornton, H. R., Z. R. Wolanski, "Lubrication with Electrodeposited Films of Silver-Rhenium and Gold-Molybdenum," Lubrication Eng. 23, 271-7 (July 1967).

Tlamsa, J., and J. Nussberger, "On the Action of Organic Vapours on Contact Materials in Telecommunication Equipment," Nachrichtentechnik (Germany), Vol. 13, No. 7, 272-7 (July 1963). In German.

Tödt, F., R. Freier and W. Schwarz, "Die Messung der Oxydationsgeschwindigkeit und Oxydschichtdicke von Metalloberflächen sowie der Lokalelementtätigkeit zwischen Metall und Metalloxyd," Zeitschrift für Elektrochemie, 53, 132-42 (1949).

Torseke, L., and T. E. Thorsteinsen, "The Influence of Pollution on the Characteristics of Lightning Arresters. Theoretical Aspects and Artificial Tests.", Conference Internationale des Grands Reseaux Electriques Paris, 1966 (Paris: Conference Internationale des Grands Reseaux Electriques, 1966) Paper No. 404.

Tripp, J. H., R. F. Snowball, and J. B. P. Williamson, "Nature of Electrical Contact between Tarnished Surfaces," Journal of Applied Physics, Vol. 38, No. 6, pp. 2439-41, May 1967.

Tsuboi, M., "Some Experimental Studies on Electrical Contacts of (Railway) Signalling Relays," Bull. Internat. Railway Congr. Assoc., Vol. 40, No. 10, 677-82, (Oct. 1963).

Turner, T. Henry, "Mainly Metallurgy," The Engineer, Vol. 217, pp.274-5, Feb. 7, 1964.

Turner, H. W., and C. Turner, "Contact Materials, Their Properties and Uses, Part 2," Electrical Times, Vol. 152 (8), pp. 277-81, Aug. 24, 1967.

Tuttle, George A., "Investigation of Dielectric Strength and Surface Current Leakage of Leaflet II High Voltage Connectors," Army Tank-Automotive Center Warren Mich., Final Report No. 4042, October 1957, 7 pp.

Uhlig, H. H., I.-Ming Feng, W. D. Tierney, and A. McClellan, "A Fundamental Investigation of Fretting Corrosion," Natl. Advisory Comm. Aeronaut., Tech. Note No. 3029, 52 pp. (1953).

Ulbricht, "Contact Problems in Electronic Measuring Apparatus," Radio Mentor (Germany), Vol. 33, No. 10, 786-9 (Oct. 1967). In German.

Ulsh, Holmes B., "Electrical Characteristics of Oxide Films on Copper Base Materials Before Electrical Breakdown and Contact Resistance After Electrical Breakdown," Proc. for Engineering Seminar on Electrical Contacts, Penn. State Univ., June 1957, 22 pp.

Ulsh, H. B., "Current Ideas in the Philosophy of Testing Electrical Contacts," IEEE Trans Pts Materials Packaging (USA), Vol. PMP-2, No. 3, 68-70, (Sept. 1966).

Van Brunt, C., and R. H. Savage, "Carbon-Brush Contact Films: Part I. Collector Films Largely Determine Brush Performance. How They Are Critically Affected by High Altitudes," General Electric Rev. 47, 16-19 (July 1944).

Van Brunt, C., "Carbon-Brush Contact Films: Part II. Striking Effect of Oxygen on Cuprous Oxide Contact Films. Adjuvants, or Substitutes, for Film Carbon Lubrication at High Altitudes? What Experiments with Brass Collectors Have Taught," General Electric Review, pp. 28-35, August 1944.

Vernon, W. H. J., "Second Experimental Report to the Atmospheric Corrosion Research Committee (British Non-Ferrous Metals Research Association)", Faraday Soc. Trans. 23 , 113 - (1927).

Vernon, W. H. J., "Properties of Sulphide Films," Trans. Faraday Society, 23, 133-5 (1927).

Vernon, W. H. J., "Effects Produced by 'Smoke Films'", Trans.Faraday Soc., 23, 135-40 (1927).

Vernon, W. H. J., "A Laboratory Study of the Atmospheric Corrosion of Metals," Trans. Faraday Soc. 27, 255-77 (1931).

Vernon, W. H. J., "The 'Fogging' of Nickel," J. Inst. of Metals 48, 121-45 (1932).

Wagar, H. N., "The Making of a Good Contact," Bell Laboratories Record, No date.

Walsh, J. J. and H. F. Church, "Investigation of Deterioration of Moulded Carbon Resistors: Second Report," The Electrical Research Association, Technical Report Z-T96, 1955.

Walton, R. F., "Effect of Type and Porosity of Gold Deposits on the Contact Resistance of Electroplated Materials," Plating 53 (2), 209-16 (1966).

Waste, Werner, "Erkenntnisse aus der Störungs - und Schadensstatistik für Drehstromschaltanlagen," (Conclusions Drawn from Breakdown and Damage Statistics for A.C. Switchgear Installations), Elektrotechnische Zeitschrift (ETZ) A 83 (6), 164-71 (March 12, 1962).

Went, J. J., "Adsorption Phenomena on Massive Metal Surfaces Measured by Means of Electrical Contact Resistances," Physica VIII, No. 2, pp. 233-50, Februari, 1941.

Whitehead, J. R., "Surface Deformation and Friction of Metals at Light Loads," Proc. Royal Society A, 201, 109-24 (1950).

Whitley, J. H., "Basic Contact Theory vs Practical Experience in Electrical Connections," Proc. Engineering Seminar on Electrical Contacts, Univ. Maine, Orono, Maine, 1965, pp. 29-43.

Wick, Reyburn W., and Anthony Gallaccio, "Review of Factors Influencing Electrical Resistance and Functioning of Low Voltage Relay Switch Contacts," Frankford Arsenal Philadelphia Pa Research and Development Directorate, Report No. MR-M65-7-1, Dec. 1964, 13 pp.

Wikell, Göran, "Approach to the Analysis of the Dynamic Phenomena Occurring at Contact-Make in a Simply Built Flexure-Operated Relay-Spring Assembly with Springs of a Simple Geometric Form," Tele (Sweden) 16 (1), 15-31 (1964).

Williams, J. C., and D. B. Herrmann, "Surface Resistivity of Nonporous Ceramic and Organic Insulating Materials at High Humidity with Observations of Associated Silver Migration," IRE Trans. Reliability and Quality Control, No. PGRQC-6, 11-20 (Feb. 1966).

Williams, T. R. G., and D. T. Stevens, "Failure of Armature Arms in Electrical Relays," Engineer (GB) 224, 826-7 (Dec. 22, 1967).

Williamson, J. B. P., "Characteristics of Contact Surfaces to Make Reliable Electrical Connections," Machine Design 36, (11), 172+ (1964).

Williamson, J. B. P., "Basic Properites of Electric Contacts," Proc. Engineering Seminar on Electrical Contacts, Univ. Maine, Orono, Maine, 1965, pp. 3-13.

Wilson, R. W., "The Contact Resistance and Mechanical Properties of Surface Films on Metals," Proc. Phys. Soc. LXVIII, 9-B, pp. 625-41 (1955).

Wilson, W. R., "Life of Silver-Surfaced Contacts on Repetitive Arcing Duty," Power Apparatus and Systems, pp. 1236-43 (Dec. 1953).

Wilson, W. R., "High-Current Arc Erosion of Electric Contact Materials," Amer. Inst. Elect. Engrs., Trans., Power Apparatus & Syst., No. 19, 657-64 (Aug. 1955).

Wollenek, Anton, "Symmetrische und unsymmetrische versilberte Starkstrom-Punktkontakte," (Symmetrical and Unsymmetrical Silvered High Current Contact Points), Elektrotechniche Zeitschrift (ETZ) A 80 (23), 826-7 (Dec. 1, 1959).

Wood, R. and G. H. Wyatt, "An Instance of Corrosionin Electric Relays," J. Soc. Chem. Ind. 62, 110-11 (1943).

Yamamoto, Mitsuyoshi and Kenzo Ohashi, "Salt Contamination of External Insulation of High-Voltage Apparatus and Its Countermeasures," AIEE Trans - Power, App. Systems, pp. 380-7 August 1961.

Yates, L. D., "Corrosion Tests of Metals and Ceramics," Tennessee Valley Authority, Chemical Engineering Report No. 9, 56 pp., 1951.

Zalabák, J., "Telephone Equipment for the Tropics," Slaboproudy Obzor, Vol. 20, No. 8, 476-81 (1959). In Czech.

Zoledziowski, S. "Time-to-Flashover Characteristics of Polluted Insulation," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-87, No. 6 6, June 1968, pp. 1397-1404.

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16. Abstracts
Prevention of contact failure in low voltage contacts is the largest problem. Millions of low voltage contacts are used in computer and instrumentation circuits, and some provision must be made to ensure their reliable and continued operation. The sulfur gases are primarily responsible for the deleterious effect of air pollution on these contacts. More money is spent in the protection of low voltage contacts against the effects of sulfur gases than in all the other contact problem areas combined. Protection of low voltage contacts against sulfur gases takes two forms: the use of air conditioning and air purification equipment; the other kind of protection of contacts against sulfur gases is precious metal plating. The cost relating to failure of electrical devices caused by air pollution for 1968 is estimated to be about $64 million in the United States. Reducing current air pollution by 50 percent would have little effect on air pollution costs related to electrical devices, because any reduced level of recognized air pollution would still require that measures taken to combat air pollution effects be continued at the same level of effort. Industry does not know the amount of air pollution reduction needed to appreciably reduce the damaging effects on electrical contacts.

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Hydrocarbons
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Low Voltage
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